• **Plate 1**

In this great institution, supported by the Government of Canada, important researches in physics and chemistry are made. These researches are chiefly on problems relating to agriculture and industry including aeronautics and radio. The Council was organized in 1916; this building was completed in 1932. In the foreground is the Rideau River.

ELEMENTS OF PHYSICS
FOR CANADIAN SCHOOLS

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PREFACE

This work appeared first in 1911 as the *Ontario High School Physics*. A second edition was issued in 1923 under the same name which however later was changed to the *Elements of Physics*. To this title has now been added "for Canadian Schools," the reason why being quite evident to anyone examining the book; for while it certainly is not provincial or narrowly national in outlook, a Canadian atmosphere is given to it by means of its illustrations.

This new edition has been thoroughly revised. Some sections have been eliminated, others rewritten, and also considerable additions have been made. These additions are chiefly in the portion devoted to Electricity, in which new discoveries and practical applications are continually being made; and to the part dealing with Sound. For some years this branch of science was pushed into the background, but recently its wonderful applications to moving pictures and to radio, and also the gratifying revival of music in our schools has created fresh interest in Sound. Music is receiving greater attention in all grades of educational institutions and a graduating course embodying a large amount of music has been established in one of our universities.

The order in which the different branches of Physics are treated has been changed, following the experience gained in teaching the subject, and for the same reason the chapters have been shortened and increased in number.

References to agriculture, still our greatest national business, have been made in many places.

Some of the old diagrams have been omitted and many new ones added. They have been drawn specially for this work and the total number is exceptionally large. In treating the various topics in the text an attempt has been made to give clear logical explanations, not just a picture with a general statement.

It is believed that special interest will be aroused by the plates distributed through the book. For the original photographs from which they were made, thanks are tendered to the various persons and firms which supplied them. Some of the photographs were taken expressly for this work.

The short tables of physical constants to be found in almost every chapter have been compiled from the *Smithsonian Physical Tables*. published by the Smithsonian Institution, Washington, D.C. This useful volume should be in every school.

Toronto, August 1937. C.A.C.

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• *Indicates legend on back of illustration.*

TABLE OF EQUIVALENTS OF UNITS

LENGTH

1 in. = 2·54 cm.	1 cm. = 0·3937 in.
1 ft. = 30·48 cm.	1 m. = 39·37 in. = 1·094 yd.
1 yd. = 91·44 cm.	1 km. = 0·6214 mi.
1 mi. = 1·609 km.	1 km. = 1000 m., 1 m. = 100 cm.,
	1 cm. = 10 mm.

SURFACE

1 sq. in. 6·4514 sq. cm.	1 sq. cm. = 0·1550 sq. in.
1 sq. ft. 929·01 sq. cm.	1 sq. m. = 10·764 sq. ft.
1 sq. yd. 0·83613 sq. m.	1 sq. m. = 1·196 sq. yd.

VOLUME

1 c. in. = 16·387 c.c.	1 c.c. = 0·061 c. in.
1 c. ft. = 28317 c.c.	1 l. = 1000 c.c. = 61·024 c. in.
1 c. yd. = 0·7645 cu. m.	1 cu. m. = 1·308 c. yd.

1 Imperial gallon	= 10 lb. water at 62° F.
	= 277·274 c. in. = 4·546 l.
1 c. ft. water	= 62·4 lb. at 4° C. or 39·2° F.
1 Imperial quart	= 1·136 l.
1 U.S. gallon	= 231 c. in. = 3·784 l.
1 l.	= 1·7598 Imperial pints.

MASS

1 lb. av. (7000 gr.) = 453·59 gm.	1 kg. = 2·205 lb. av.
1 oz. av. = 28·3495 gm.	1 gm. = 15·432 gr.
1 gr. = 0·0648 gm.	

ABBREVIATIONS

in. = inch; ft. = foot; yd. = yard; mi. = mile; sq. = square; c. or cu. = cubic; m. = metre; mm. = millimetre; cm. = centimetre; km. = kilometre; c. cm. or c.c. = cubic centimetre; l. = litre; lb. av. = pound avoirdupois; gr. = grain; gm. = gram; kg. = kilogram.

PART I—INTRODUCTION

CHAPTER I

INTRODUCTORY IDEAS

1. Why We Study Physics. The various operations of nature are continually before our eyes, and by the time that we definitely enter upon the study of physics, we have gathered a store of observations and experiences.

We all know the great service which the waterfalls of our country give us. They generate electricity which, after being transmitted over considerable distances, lights our homes and supplies motive power for our factories and street railways. We also know how steam drives the giant ships and railway trains, which carry the commerce of the nations. The automobile is now considered indispensable, and the aeroplane is of outstanding value in exploration and wherever rapid transportation is essential. Then we have the X-ray, the radio and the spectroscope which reveals the nature of the distant stars. Ours is a wonderful age.

The study of physics is intended to enable us to understand clearly the basic principles underlying the construction and operation of these and other contrivances. In order to do this we must investigate the numerous phenomena observed in mechanics, heat, electricity, and other branches of physics; and in all these fields of study we shall find ourselves dealing with matter and energy.

2. The Three States of Matter. Matter is usually defined to be anything which occupies space, and we are all familiar

with the fact that it may exist as a **solid**, a **liquid** or a **gas**. We know, for example, that if we cool water sufficiently it becomes a solid (ice), while if we heat it above a certain temperature we obtain a gas (steam). We know also that at ordinary room temperature iron is a solid, water is a liquid and air is a gas.

When we consider how we distinguish between solids and liquids we realize at once that the main difference lies in the tendency of a liquid to flow. It must be kept in a container and it takes the shape of the containing vessel, while a solid resists any force tending to change its shape.

But gases are **fluids** also. Illuminating gas, like water, flows to our homes through pipes; and if a gas tap by mistake is left open, we soon smell the gas in all parts of the room. Evidently we must find some property of a gas which will distinguish it from a liquid.

Let us adapt a bicycle pump in the way shown in Fig. 1, making sure that air does not leak past the piston on the down-stroke. If we plug the outlet and then push down on the handle, we find that the air is easily compressed. If we release the handle, the compressed air acts like a spring and pushes the handle up again. If however we repeat the experiment, using a liquid or a solid below the piston, we cannot push the handle down at all, and we find that liquids and solids are, for all practical purposes, incompressible.

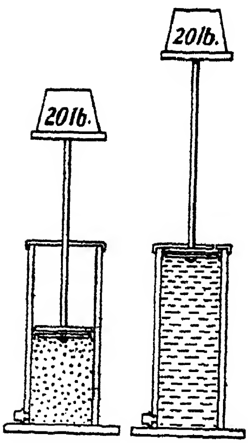


FIG. 1.—Air is easily compressed; water is not.

Moreover, a gas tends to expand and to fill any container into which it is admitted, while such is not true for a liquid or a solid.

We conclude then that the distinguishing properties of the three states of matter are the following:

Solids have definite volume and definite shape.

Liquids have definite volume but no definite shape.

Gases have neither definite volume nor definite shape.

3. Matter is Indestructible. Simple changes in matter, such as the freezing of water or the expansion and contraction of the mercury in a thermometer, are called **physical changes.** Here, there may be a change in form or in state but the substance remains identically the same.

When iron rusts, however, or coal burns, new substances with new properties are formed. These are **chemical changes,** and we might be inclined to think that such changes indicate that matter may be destroyed. But the skilful chemist can recover the iron from the iron rust. Also he can prove that when coal is burned there is just as much matter, or mass, in what comes from the combustion as there was in the coal and oxygen which united chemically when the coal was consumed. Man can not destroy matter nor can he create it.

4. Energy. To push down the handle of the bicycle pump in § 2 we had to exert **force** through a **distance,** and we say that we did a certain amount of **work.** As a result of this work, the compressed air possesses **energy** or **ability to do work.** For example, compressed air may be used to run an engine or to operate machines for drilling rock. Similarly a bent bow (Fig. 2), or a wound-up clock-spring, possesses energy; the bow, when released, propels the arrow a long distance, and the clock-spring turns the wheels of the clock.

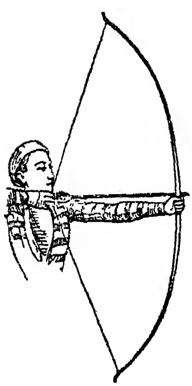


Fig. 2.—A bent bow possesses energy.

Matter in motion also possesses energy. when we drive a nail into a board we give the hammer head considerable velocity,

and work is done in pushing the nail into the board. Similarly in blacksmith shops and in iron plants, large hammers are used in shaping red-hot iron or steel.

We say that the bent bow and the wound-up spring have **potential energy**, while the moving hammer has **kinetic energy**. These are examples of mechanical energy, but later we shall study something about energy in the form of heat, light, sound and electricity.

5. The Conservation of Energy. A long series of experiments has led physicists to believe that energy, like matter, is indestructible. Man may invent machines such as the steam-engine, which converts heat energy into mechanical energy, or the dynamo, which turns mechanical energy into electrical energy, but he cannot create energy or destroy it.

This statement or idea is called the **Law of Conservation of Energy.**

From the above definitions of matter (or mass) and energy it would appear that they are entirely different in nature, but in recent years reasons have been found for believing that they are not so different after all. It has long been recognized that energy is always associated with mass; the modern view is that mass may actually be transformed into energy, and that it does not require much mass to produce a great deal of energy.

QUESTIONS

1. How would you show that air occupies space?
2. Give three examples of (*a*) physical change, (*b*) chemical change.
3. What transformations of energy take place when
   (*a*) Coal is burned to drive a steam-engine,
   (*b*) A piece of lead gets hot on being hammered,
   (*c*) An electric current drives a motor,
   (*d*) A water motor drives a dynamo,
   (*e*) A lead bullet hits an iron plate?
4. When we burn coal to heat our homes we are utilizing energy which came from the sun millions of years ago. Explain.

CHAPTER II

MEASUREMENT—THE YARD, THE METRE

6. The Need for Measurement. All scientific investigations, and indeed many of the activities of our everyday life, are concerned with careful measurement. We pay for our gasoline by the measured gallon and the cautious driver desires to know how many miles his car will run per gallon. In buying a car he enquires about the horse-power of the engine, and when his tires are inflated the garage man uses a gauge to ensure that the pressure is the proper number of pounds per square inch. In heating our houses we are guided by the indicated temperature, and we pay for gas and electricity according to the readings on certain meters. It is obvious that, if we are to make any progress in life, we must learn something about measurement.

It is, of course, physically impossible for us to make a measurement of any kind with absolute accuracy. Moreover the degree of accuracy to be aimed at depends very much on what we are measuring. When a clerk sells us a yard of cloth an error of even half an inch is not very serious; but the steel balls used for bearings in automobiles and other high-class machines should not differ from one another by $\frac{1}{100000}$ inch. The farther we advance in physics, the greater becomes the necessity for precision in measurement.

7. Fundamental Units. In measuring any quantity we determine how many times a magnitude of the same kind, which we call a unit, is contained in the quantity to be measured. Thus we speak of a length being 5 feet, the unit chosen being a foot and 5 expressing the number of times the unit is contained in the given length.

There will be as many kinds of units as there are kinds of quantities to be measured, and the size of the units may be just what we choose. But there are three units which we speak of as **fundamental**, namely, the units of **length**, **mass** and **time**. These units are fundamental in the sense that each is independent of the others and cannot be derived from them; also we shall find that the measurement of any quantity—such as the power of a steam engine, the speed of a rifle-bullet or the strength of an electric current—can ultimately be reduced to measurement of length, mass and time. Hence these units are properly considered fundamental.

8. The British and the Metric Systems. There are two widely used systems of units, namely, the British and the Metric system. In the former the **foot**, the **pound** and the **second** are the units of length, mass and time, respectively. In the latter, which is used almost universally in purely scientific work, the units of length, mass and time are the **centimetre**, the **gram** and the **second**, respectively.

The former is sometimes called the F.P.S. system, the latter the C.G.S. system, the distinguishing letters being the initials of the units of the two cases.

9. Standards of Length—the Yard. There are two material standards of length in use in English-speaking countries, namely, the **yard** and the **metre**.

The yard is said to have represented, originally, the length of the arm of King Henry I (1100-1135), but such a definition is not accurate enough for present-day requirements. The crude manner in which this unit was specified at that time, compared with the precise way in which it is fixed and reproduced now, may serve to illustrate the growth in the appreciation of science by the people in the last 800 years.

The yard is now defined as the distance, at 62° F., between the centres of two transverse lines ruled on two gold plugs in a bronze bar, which is preserved in London, England, in the Standards Office of the Board of Trade of Great Britain. The bronze bar is 38 inches long and has a cross section one square (Fig. 3). At *a*, *a*, wells are sunk to the mid-depth of the bar, and at the bottom of each well is the gold plug or pin, about $\frac{1}{10}$ inch in diameter, on which the line defining the yard is engraved.

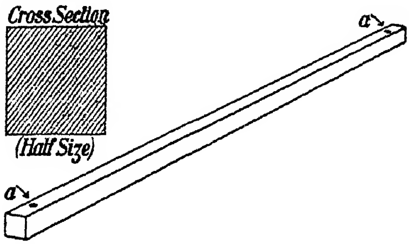
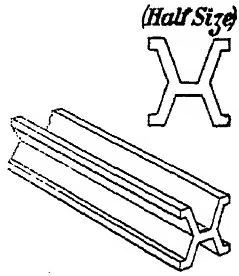


FIG. 3—Bronze yard, 38 in. long, 1 in. sq. in section; *a*, *a*, are small wells in the bar, sunk to mid-depth.

The other units of length in ordinary use, such as the inch, the foot, the rod, the mile, are derived from the yard and are called **derived** units. Unfortunately, however, they are not obtained by dividing into tenths or by multiplying by tens, and so calculations in the British system are much longer and more tedious than in the metric system.

10. The Metre. The metre came into existence through an effort made in France, at the end of the 18th century, to replace by one standard the many and confusing standards of length prevailing throughout the country. It was decided that the new standard should be one ten-millionth of the distance from the pole to the equator, measured through Paris, and years were consumed in trying to make a metal bar which should be of exactly this length. The task was completed in 1799. But since then further measurements of the earth have been made and it has been shown that the bar is a little shorter—perhaps a hair's-breadth—than it was intended to be. So now we define the metre without reference to the earth at all; it is the distance between two lines on a

metal rod which is preserved in the International Bureau of Weights and Measures at Sèvres, near Paris. The measurements are to be taken when the rod is at the temperature of melting ice. Many copies of this standard have been made and supplied to various nations. The bars are made of a hard and durable alloy composed of platinum 90 per cent. and iridium 10 per cent. and their form is shown in Fig. 4.



metre bars. The line defining the end of the metre is a short mark on the surface which is midway between the top and the bottom of the bar.

The metric system is almost universally used in scientific experiments, and it has often been proposed that the British Empire and the United States should use it in ordinary life, as almost all other nations do; but little progress toward this end has been made in the last fifty years.

11. Divisions and Multiples of the Metre. In the metric system the units are divided and multiplied decimally. The names of the sub-divisions are obtained by using the Latin prefixes, *deci* ($\frac{1}{10}$), *centi* ($\frac{1}{100}$), *milli* ($\frac{1}{1000}$); and the names of the multiples are formed with the Greek prefixes, *deca* (10), *hecto* (100), *kilo* (1000). Thus:

10 millimetres (mm.) = 1 centimetre
10 centimetres (cm.) = 1 decimetre
10 decimetres (dm.) = 1 metre
10 metres (m.) = 1 decametre
10 decametres = 1 hectometre
10 hectometres = 1 kilometre (km).

The decametre and the hectometre are not often used.

12. Relation of Metres to Yards. In Great Britain the yard is the standard, and the relation between the metre and the inch is officially stated to be:

1 metre = 39·370113 inches;

but in the United States the metre is the fundamental standard, and by law

$$1 \text{ metre} = 39\cdot37 \text{ inches.}$$

The difference between these two statements of length of the metre is only $\frac{1}{10000}$ inch, and the British and the United States yard may be considered identical.

Approximately 1 in. = $2\frac{1}{2}$ cm.; 1 ft. = 30 cm.; 5 mi. = 8 km.

In Fig. 5 is shown a comparison of centimetres and inches.

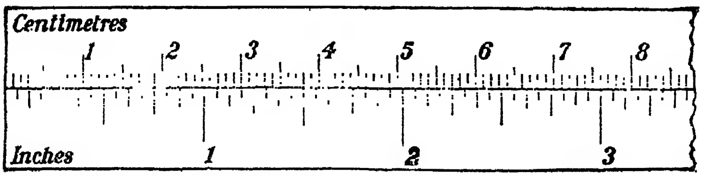


FIG. 5.—Comparison of inches and centimetres.

13. Units of Area and of Volume. The ordinary units of surface and of volume are derived from the units of length. Thus, we have the square metre (sq. m.), the square centimetre (sq. cm.), the square yard (sq. yd.), the square foot (sq. ft.), etc.; also, the cubic metre (cu. m.), the cubic centimetre (c.c.), the cubic foot (cu. ft.), the cubic inch (cu. in.), etc.

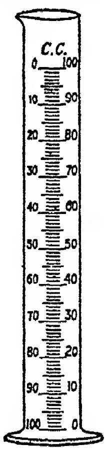


FIG. 7.—A graduated cylinder

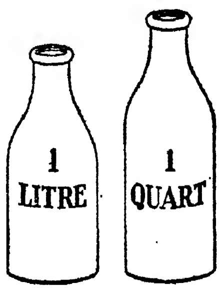


FIG. 6.—A litre is about $\frac{7}{8}$ of an imperial quart.

The imperial gallon, which is the legal standard of capacity in Canada, is defined as the volume of 10 pounds of water at 62° F., and it is equal to 277·274 cu. in. The Winchester gallon or wine-gallon, which is the common United States gallon, contains 231 cu. in. It is roughly five-sixths of the imperial gallon.

A common unit of capacity in the metric system is the litre which contains 1 cubic decimetre. Hence

$$1 \text{ litre} = 1000 \text{ c.c.}$$

The imperial quart contains, of course, two pints, while the litre is about 1·76 pints (Fig. 6).

Graduated cylinders (Fig. 7) are commonly used in science for measuring liquids.

PROBLEMS AND QUESTIONS

(For table of values see opposite page 1)

1. How many millimetres are there in $2\frac{1}{2}$ kilometres?

2. Light travels in empty space 186,284 miles in a second; express this in kilometres.

3. The floor of a building is 13×30 metres; how many square centimetres are there in it?

4. If the mercury in a barometer is 760 mm. high, what will be the height in inches?

5. Reduce 1 cubic metre to litres and to cubic centimetres.

6. Lake Superior is 602 feet above sea-level. Express this in metres.

7. Dredging is done at 50 cents per cubic yard. Find the cost per cubic metre.

8. Air weighs 1·293 grams per litre. Find in kilograms the weight of the air in a room $25 \times 20 \times 10$ metres in dimensions.

9. Which is cheaper, milk at 7 cents per litre or 8 cents per quart?

10. If gasoline costs 25 cents per gallon in Canada, what should the price (at the same rate) be in the United States?

11. The polar diameter of the earth is 12,712·9 kilometres, the equatorial diameter 12,756·4 kilometres. Give these dimensions in miles.

12. A runner goes 100 yards in $10\frac{2}{5}$ seconds; how long should he take to go 100 metres at the same speed?

13. How would you use an ordinary rule to measure the thickness of a leaf of this book? Measure it.

14. Devise a method for measuring the length of a curved line.

15. If you were given an ungraduated cylinder, how would you proceed to graduate it in cubic centimetres?

CHAPTER III

MASS AND ITS MEASUREMENT; TIME

14. Mass. If we kick, or lift, a brick and also a wooden block of the same size we realize that there is an essential difference between them, which the physicist calls a difference in mass. For lack of a better definition, we often say that the mass of a body is the **quantity of matter** in it. Matter may change its form, but it can never be destroyed. A lump of matter might be transported to the moon or to any other place in the universe but its mass would remain the same.

15. Units of Mass. There are two units of mass in common use.

In the British system the **pound** is the fundamental unit. The standard pound is a certain piece of platinum, which is preserved in the Standards Office in London, England. Its form is shown in Fig. 8.

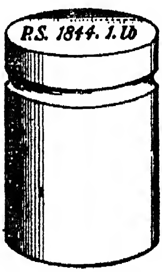


FIG. 8.—Imperial Standard Pound Avoirdupois. Made of platinum. Height 1·35 inches; diameter 1·15 inches. "P.S." stands for *parliamentary standard.*

Unfortunately the pound is not divided decimally, and the calculations which involve the pound are more complicated than those in the metric system.

In the English system

$$1 \text{ grain} = \frac{1}{7000} \text{ pound (avoirdupois).}$$

$$1 \text{ ounce} = \frac{1}{16} \text{ pound} = 437{\cdot}5 \text{ grains.}$$

Originally a grain of wheat was taken from the middle of the ear, and, after being well dried, was used as a standard *grain.*

In the metric system the fundamental unit is the **kilogram.** The world's standard kilogram is a cylinder of platinum-

iridium alloy almost exactly $1\frac{1}{2}$ inches in diameter and in height. It is preserved at Sèvres, France. A large number of equal standard masses have been made and distributed to different nations. One delivered to the United States is shown in Fig. 9.

The kilogram is divided decimally:

10 milligrams (mg.)	=	1 centigram (cg.)
10 centigrams	=	1 decigram (dg.)
10 decigrams	=	1 gram (gm.)
1000 grams	=	1 kilogram (kg.)

The decagram (10 gm.) and the hectogram (100 gm.) are seldom used.

The original kilogram was intended to represent the mass of 1000 c.c. (1 litre) of water when at its maximum density (at 4° C.)

Hence 1 c.c. water has 1 gram mass.

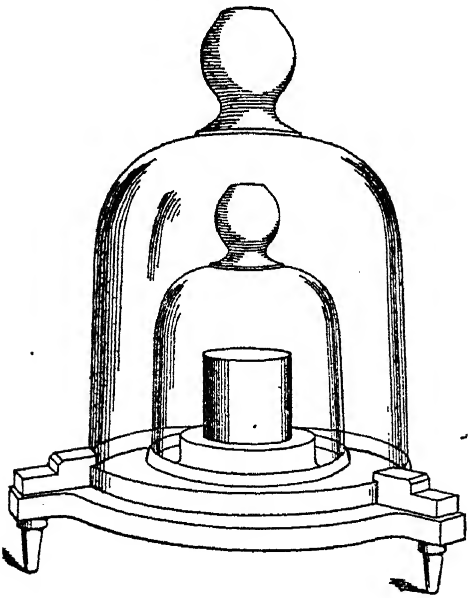


Fig. 9—United States National Kilogram. Kept under two glass bell-jars at Washington.

The relation of the pound to the kilogram is officially stated by the British government as follows:

1 kilogram (kg.) = 2·2046223 pounds avoir.
1 gram (gm.) = 15·4323564 grains.
1 pound avoir. = 0·45359243 kg.
1 ounce avoir. = 28·349527 grams.
Approximately 1 kg. = $2\frac{1}{5}$ lb.; 1 oz. = $28\frac{1}{3}$ gm.

In transforming from kilograms to pounds, or the reverse, it will not be necessary to use so many decimal places as are given here.

The equivalent values may be taken from the table opposite page 1.

16. Measurement of Mass. In Fig. 10 is shown a balance. The pans *A* and *B* are suspended from the ends of the beam *CD*, which can turn easily about a "knife-edge" at *E*. This is usually a sharp steel edge resting on a steel or an agate plate. The bearings at *C* and *D*, shown more fully in Fig. 11, are nearly frictionless, so that the beam turns very freely. A long pointer *P* extends downwards from the middle of the beam, and its lower end moves over a scale *O*. When the pans are balanced and the beam is level, the pointer is opposite zero on the scale.

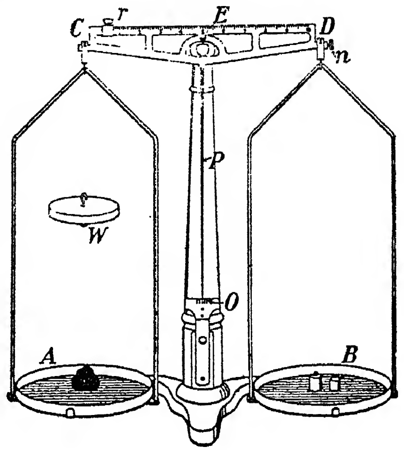


Fig. 10.—A simple and convenient balance. When in equilibrium the pointer *P* stands at zero on the scale *O*. The nut *n* is for adjusting the balance and the small weights, fractions of a gram, are obtained by sliding the rider *r* along the beam which is graduated. The mass *W*, if substituted for the pan *A*, will balance the pan *B*.

Suppose a lump of matter is placed on pan *A*. At once it descends and equilibrium is destroyed. It goes downward because the earth attracts the matter. Now put another lump on pan *B*. If it remains up, we say the mass on *A* is heavier than that on *B*; if the pans come to the same level and the pointer stands at zero, the two masses are equal.

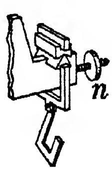


Fig. 11.—Showing end of arm of balance.

17. Mass and Weight. It is the attraction of the earth upon the masses placed upon the pans which produces the motion of the balance. **The attraction of the earth upon a mass is called its weight,** and so in the balance it is the weights of the bodies which are compared.

Let us consider further how weight differs from mass. We have already stated in § 14 that the mass of a body does not change as we move it from place to place. A standard kilogram would have the same mass in a balloon ten miles above the earth that it has on the earth's surface.

But the weight of a body depends on its distance from the centre of the earth. A sensitive spring balance (Fig. 12) would show that the weight of the kilogram mass in the balloon would continually decrease as the balloon moved farther and farther from the earth. *The weight of a body is a variable quantity; its mass is a constant quantity.*

However, as will be explained more fully in Chapter XVII, the weight of a two-pound mass at any place is twice the weight of a one-pound mass at the same place; and if two masses are equal their weights at the same place are also equal. Consequently, the balance allows us to compare masses by comparing their weights.

FIG. 12.—The weight of the body stretches the spring.

18. Sets of "Weights". We have agreed that the lump of platinum-iridium known as the International Kilogram shall be our standard of mass (§ 15).

In order to duplicate it we simply place it on one pan of the balance, and by careful filing we make another piece of matter which, when placed on the other pan, will just balance it.

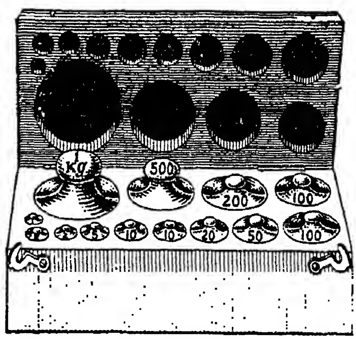


FIG. 13.—A box of weights.

Again, with patience and care, two masses can be constructed which will be equal to each other, and which, taken

together, will be equal to the original kilogram. Each will be 500 grams.

Continuing, we can produce masses of other denominations, and we may end by having a set consisting of

1,000, 500, 200, 100, 100, 50, 20, 10, 10, 5, 2, 2, 1 grams

and even smaller masses.

A set of these masses (Fig. 13) is usually called a "set of weights" although, as we have seen in § 17, the term weight should be restricted to the pull of the earth on a mass.

If now a body is placed on pan *A* of the balance, by proper combination of these masses we can balance it and thus at once determine its mass.

The balance and the "weights" used by merchants throughout the country are periodically inspected by a government officer.

19. Rules for the Use of the Balance.

1. Keep the balance dry and free from dust.

2. See that the balance is properly adjusted, so that it will, when unloaded, either rest in equilibrium with the pointer at the zero mark on the scale, or will swing equally on either side of zero.

In the balance shown in Fig. 10 any addition under 10 grams is obtained by sliding the rider *r* along the beam. It gives $\frac{1}{10}$ gram directly, and $\frac{1}{10}$ of this may be obtained by estimation.

Before beginning, push the rider over to its zero mark, and then if the pans do not balance, as indicated by the pointer *P*, turn the nut *n* until they do.

3. Place the body whose mass is to be ascertained in the left-hand scale-pan, and place the weights in the right-hand scale-pan. Until some experience in judging the mass of a body has been obtained, try all the weights in order, commencing with the largest and omitting none. When any weight causes the right-hand pan to descend, remove it. Never select weights at random.

4. To determine the equilibrium do not wait until the balance comes to rest. When it swings equally on either side of zero, the mass in one pan equals that in the other.

5. Place the largest weight in the centre of the pan, and the others in the order of their denominations.

6. Keep the pans supported when weights are to be added or taken off.

7. Small weights should not be handled with the fingers. Use forceps.

8. Weigh in appropriate vessels substances liable to injure the pans. For counterpoise use shot and paper.

9. Never use the balance in a current of air.

20. Density. Let us take equal volumes of lead, aluminium and wood. These may conveniently be cubes measuring about 3 cm. along each edge.

By simply holding them in the hand we recognize at once that these bodies have different weights and, therefore, different masses. With the balance and our set of weights we can accurately determine the masses. Let us do this and then calculate the mass of 1 c.c. of each substance. Our results are given in the adjoining table.

Substance	Volume	Mass	Mass of unit volume
Lead	27 c.c.	306·18 gm.	11·34 gm. per c.c.
Aluminium	27 "	73·44 "	2·72 " " "
Maple	27 "	18·36 "	0·68 " " "

The mass per unit volume of a substance is its density.

Thus the density of water in the metric system is 1 gm. per c.c., and in the British system 62·4 lb. per cu. ft. at 4° C.

Consider a piece of aluminium of volume 150 c.c. Since its density is 2·72 gm. per c.c., its mass must be 150 × 2·72 gm. = 408·0 gm.

Hence we have the relation,

$$\text{Mass} = \text{Volume} \times \text{Density}.$$

Question.—If you were given a cylindrical tin can, a rule and a balance, how would you proceed to find the density of water?

21. Table of Densities. The densities of some common substances are given in the following table:

TABLE OF DENSITIES

(In grams per cubic centimetre)

Water...........	1·00	Aluminium (wrought)	2·72	Paper (average)....	0·9
Sea-water........	1·02	Butter............	0·86	Platinum..........	21·45
Alcohol (ethyl)....	0·79	Chalk.............	2·4	Silver (wrought)....	10·56
" (methyl)...	0·81	Copper (wrought)..	8·90	Tungsten..........	19·12
Chloroform.......	1·48	Diamond..........	3·5	Zinc (cast)........	7·10
Hydrochloric Acid.	1·16	Glass (ordinary)....	2·6	Cork (average).....	0·24
Sulphuric Acid....	1·84	Gold (wrought)....	19·34	Birch wood (average)	0·64
Lamp Oil (Kerosene)	0·82	Ice................	0·90	Cedar (average)....	0·53
Gasoline, about...	0·7	Iridium...........	22·10	Maple (average)....	0·68
Olive Oil.........	0·92	Iron (wrought).....	7·85	Oak (average).....	0·75
Mercury.........	13·60	Lead..............	11·34	White Pine........	0·42

22. Unit of Time. If we reckon from the time when the sun is on our meridian (noon), until it is on the meridian again, the interval is a *solar day.* But the solar days thus determined are not all exactly equal to one another. The reason for this is explained in works on astronomy. In order to get an invariable interval we take the average of the solar days and call the day thus obtained a *mean solar day.* Dividing this into 86,400 equal parts we call each a *mean solar second.* This is the quantity which is "ticked off" by our watches and clocks. It is used universally by scientific men as the fundamental unit of time.

CHAPTER IV

MEANING OF SPECIFIC GRAVITY

23. Density and Specific Gravity. As we have just seen, the density of a body is its mass per unit volume.

gravity of a substance is the ratio which the
volume of it bears to the weight of an

$$\text{Or, specific gravity} = \frac{\text{weight of body}}{\text{weight of equal volume of water}}$$

As this is just a ratio it is expressed by a simple number, and is independent of any system of units.

The specific gravity of water is, of course, 1; and when we say the specific gravity of gold is 19·34, we mean that gold is 19·34 times as heavy as water.

Next, let us consider a sample of wrought iron, 50 c.c. in volume. By the balance it is found to weigh 392·5 grams, and its density is, therefore, $392\cdot5 \div 50 = 7\cdot85$ grams per c.c.

But the weight of 50 c.c. of water = 50 grams, and the specific gravity of the iron is, therefore, $392\cdot5 \div 50 = 7\cdot85$, which is the same number as we had before.

Thus we see that in the C.G.S. system of units the density of a substance and its specific gravity are expressed by the same number.

In the F.P.S. system, however, the density of the iron would be $62\cdot4 \times 7\cdot85 = 489\cdot8$ lb. per cu. ft.

24. Specific Gravity of any Solid. To find the specific gravity of any solid it is evident that we must find its weight and also the weight of an equal volume of water.

If the solid is of regular shape we can measure its dimensions and calculate its volume. The weight of an equal volume of water can then be calculated.

Example.—Rectangular block of birch. Weight of block (by balance) $= 256$ gm. Length $= 10$ cm., width $= 8$ cm., height $= 5$ cm. Volume $= 10 \times 8 \times 5 = 400$ c.c. Weight of equal volume of water $= 400$ gm.

$$\text{S.G. of birch} = \frac{256}{400} = 0\cdot64.$$

If however the solid is of irregular shape, say a piece of stone, we must adopt another method to find the weight of an equal volume of water. A suitable arrangement is the overflow can shown in Fig. 14. The can is filled with water until the water is just level with the spout. Then the stone is lowered into the can without splashing, and the overflow is caught in the catch-bucket, which has previously been weighed. Since the water which overflows has the same volume as the stone, we have only to weigh the bucket and water and then subtract the weight of the bucket.

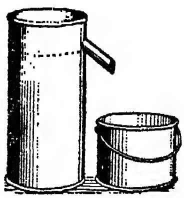


FIG. 14.—Overflow can.

Question.—If the irregular solid is of a material which floats in water, how would you find the weight of the equal volume of water?

25. Specific Gravity of a Liquid by the Specific Gravity Bottle. As in the case of solids, the problem is to determine the mass of the liquid and the mass of an equal volume of water.

In Fig. 15 is shown a convenient bottle to use. It is provided with a closely-fitting stopper perforated with a fine bore through which any excess of liquid escapes.

FIG. 15.—Specific gravity bottle.

First, the bottle is weighed empty; then it is filled with water and weighed; then filled with the liquid and weighed again.

Example.—A bottle empty weighed 21·10 gm.; when filled with water, 71·22 gm.; when filled with alcohol, 61·73 gm. Find the S. G. of the alcohol.

Weight of the water filling the bottle = 50·12 gm.
Weight of the alcohol filling the bottle = 40·63 "

$$\text{Hence, the S.G. of the alcohol} = \frac{40\cdot 63}{50\cdot 12} = 0\cdot 81.$$

In Chapter VII we shall discuss another method of determining the specific gravity of a solid or a liquid.

PROBLEMS AND QUESTIONS

1. Find the mass of 140 c.c. of silver if its density is 10·5 gm. per c.c.

2. The specific gravity of sulphuric acid is 1·85. How many c.c. must one take to weigh 100 gm.?

3. A piece of granite weighs 83·7 gm. On dropping it into the water in a graduated vessel, the water rises from 130 c.c. to 161 c.c. (Fig. 16). Find the density of the granite. What is its specific gravity? Find the density in the British system.

4. A tank 50 cm. long, 20 cm. wide and 15 cm. deep is filled with alcohol of density 0·8 gm. per c.c. Find the weight of the alcohol.

5. A rectangular block of wood 5 × 10 × 20 cm. in dimensions weighs 770 grams. Find the density. What is the specific gravity of the wood? Find its density in the British system.

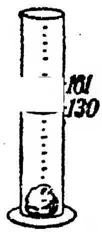


Fig. 16.

6. A bottle empty weighed 32·4 grams; when filled with water, 77·7 grams; when filled with alcohol, 68·6 grams. Find the specific gravity of the alcohol.

7. The specific gravity of pure milk is 1·086. What is the density of a mixture containing 500 c.c. of pure milk and 100 c.c. of water?

8. A rolled aluminium cylinder is 20 cm. long, 35 mm. in diameter, and its density is 2·7 gm. per c.c. Find the weight of the cylinder.

9. The density of platinum is 21·5, of iridium is 22·4, gm. per c.c. Find the density of an alloy containing 9 parts of platinum to 1 part of iridium. Find the volume of 1 kg. of the alloy.

10. A thread of mercury in a fine cylindrical tube is 28 cm. long and weighs 11·9 grams. Find the internal diameter of the tube.

11. State some of the advantages of the metric system of weights and measures.

REFERENCES FOR FURTHER INFORMATION

Articles on "Metric System" and "Weights and Measures" in the *Encyclopedia Britannica.*

A ROOM IN THE ONTARIO RESEARCH FOUNDATION, QUEEN'S PARK, TORONTO

Plate 2

● **Plate 2**

Silk yarn to be used in insulating electrical conductors is being tested in this apparatus. The yarn is in a bottle in the tank at the left and is exposed to moist air. Voltage is applied to the silk from the batteries and the resulting current through the silk is measured by the galvanometer in the alcove in front of the experimenter.

PART II—MECHANICS OF FLUIDS

CHAPTER V

PRESSURE OF LIQUIDS

26. Pressure of a Fluid. It is a matter of common experience that a liquid exerts a force upon the surface with which it is in contact. It is this force which makes a ship float and which is utilized in hydraulic brakes and in many other useful appliances.

We know also that gases exert such a force. When we inflate our tires at a service station, the air flows into the tires because the pressure in the compressed air tank is greater than that in the tires. For a similar reason a tire goes "flat" when we have a puncture. Let us see just what the term "pressure" means.

27. Pressure: How Measured. A wooden tank, such as we often see above buildings for fire-protection purposes, or beside the railway for supplying water to the locomotives, is bound with strong iron bands to prevent the water from pushing the staves outwards. We note, also, that the bands are closer together near the bottom than higher up, indicating that the pressure at the bottom is greater than near the top.

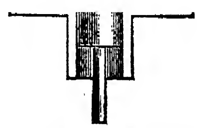


FIG. 17.—Pressure at the bottom of a vessel.

Consider a vessel like that in Fig. 17, having a piston inserted in the bottom. A force must be applied upwards on the piston

to prevent the water from pushing the piston out. Let the force upwards required to balance the pressure of the water be 10 pounds, and the area of the piston be 5 square inches. Then the pressure of the water on the piston is 2 pounds per square inch.

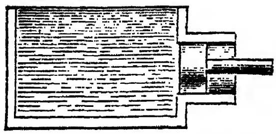


FIG. 18.—Pressure at the side of a vessel.

Next consider the case of a piston of the same size inserted in the side of the vessel (Fig. 18). As remarked above, the water exerts a force upon the piston. If we adjust the depth of the water so that, as before, the force required to balance the pressure of the water is 10 pounds, then the **average pressure** of the water on the piston is 2 pounds per square inch. In this case it is necessary to say average pressure because of the fact of experience mentioned above, that the pressure depends upon the depth and so is not uniform over the surface of the piston. The manner in which the pressure varies with the depth will be taken up in § 34.

In specifying a pressure always give the force on unit area; as, pounds per square inch, grams per square centimetre, or tons per square yard.

28. Transmission of Pressure by Fluids. One of the most characteristic properties of matter is its power to transmit force. The harness connects the horse with its load; the piston and connecting rods convey the pressure of the steam to the driving wheels of the locomotive. Solids transmit pressure only in the line of action of the force. Fluids act differently. If a globe and cylinder of the form shown in Fig. 19 is filled with water and a force exerted on the water by means of a piston, it will be seen that the pressure *is transmitted*, not simply in the direction in which the force

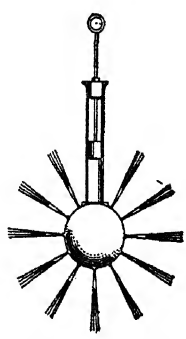


FIG. 19.—Pressure applied to the piston transmitted in all directions by the liquid

is applied, but *in all directions*; because jets of water are thrown with velocities which are apparently equal from all the apertures. If the conditions are modified by connecting with the globe U-shaped tubes partially filled with mercury, as shown in Fig. 20, it will be found that when the piston is inserted, the change in level of the mercury, caused by the transmitted pressure, is the same in each tube. This would show that the pressure applied to the piston is transmitted *equally* in all directions by the water.

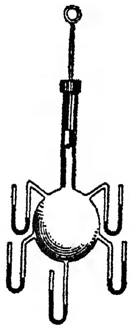


FIG. 20.—Transmission shown to be equal in all directions by pressure

Now, if the water is removed and the piston pressed gently into the cylinder, when the cylinder-and-globe is filled with air, the mercury gauges again indicate that the pressure applied to the piston is being transmitted equally in all directions. It appears, therefore, that the principle is true of gases (air) as well as liquids (water).

These facts may be expressed concisely as follows: **Pressure exerted anywhere on the mass of fluid filling a closed vessel is transmitted undiminished in all directions, and acts with the same force on all equal surfaces in a direction at right angles to them.** The principle was first enunciated by Pascal, and is generally known as **Pascal's Law or Principle.***

29. Practical Applications of Pascal's Principle. Pascal himself pointed out how it was possible, by the application of this principle, to multiply force for practical purposes. By experimenting with pistons inserted into a closed vessel filled with water, he showed that the pressures exerted on the pistons when made to balance were in the ratio of their areas. Thus if the area of piston *A* (Fig. 21) is one square centimetre, and that of *B* ten times as great, one unit of force

*It appears in Pascal's *Traité de l'équilibre des liqueurs*, written in 1653, but first published in 1663, one year after the author's death.

applied to A will transmit ten units to B. It is evident that this principle has almost unlimited application. Pascal remarks "Hence it follows that a vessel full of water is a new principle of Mechanics and a new machine for multiplying forces any degree we choose."

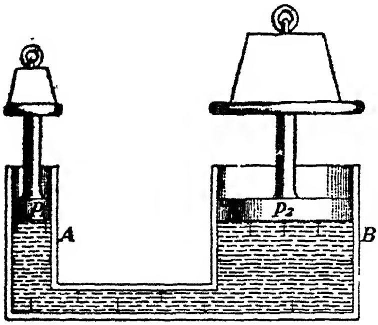


FIG. 21.—Illustrating how force may be multiplied by transmission of pressure.

The same effect may, of course, be secured by the transmission of pressure by other fluids. The use of air for this purpose may be illustrated by the apparatus shown in Fig. 22.

The cylinder C, about 5 in. in diameter, is provided with a tightly-fitting piston L. On this a heavy mass (50 pounds) is placed. One end of a piece of heavy rubber tubing is attached to C while the other end, by means of an ordinary bicycle tire valve, is joined to the bicycle pump P. On working the pump the mass is raised with very little effort. Careful experiments with similar apparatus show that (neglecting friction) if the area of L is 50 times that of the piston of the pump, only one pound force need be applied to the pump to raise the 50-pound mass.

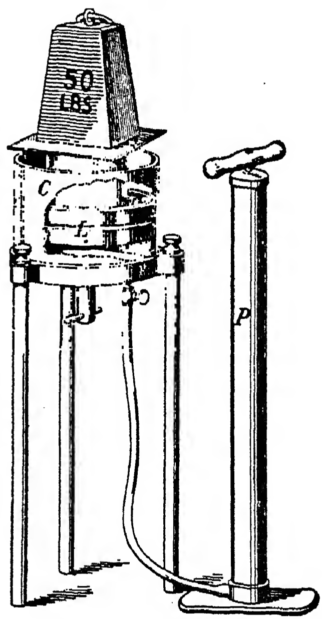


FIG. 22.—Illustrating transmission of pressure by a gas (air).

Since Pascal's time his "new machine" has taken many forms adapted to a variety of purposes. Some of the more typical

forms and applications are discussed in the remaining sections of this chapter.

30. **Hydraulic Press.** One of the most common forms is that known as Bramah's hydraulic press, which is ordinarily used whenever great force is to be exerted through short distances, as in pressing goods into bales, extracting oils from seeds, making dies, testing the strength of materials, etc. Its construction is shown in Fig. 23. A and B are two cylinders connected with each other and with a water cistern by pipes closed by valves V_1 and V_2. In these cylinders the pistons P_1 and P_2, work through water-tight collars, P_1 being moved by a lever. The bodies to be pressed are held between plates C and D. When P_1 is raised by the lever, water flows up from the cistern through the valve V_1 and fills the cylinder A. On the down-stroke the valve V_1 is closed, and the water is forced through the valve V_2 into the cylinder B, thus exerting a force on the piston P_2, which will be as many times that applied to P_1 as the area of the cross-section of P_2 is that of the cross-section of P_1. It is evident that by decreasing the size of P_1, and increasing that of P_2, an immense force may be developed by the machine. While this is true, it is to be noted that the upward movement of P_2 will be very slow, because the water displaced by P_1 during each stroke will cause P_2 to rise a very short distance compared with the distance through which P_1 moves.

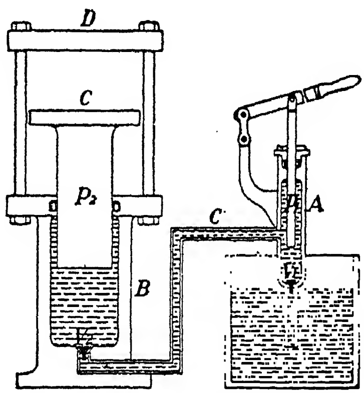


FIG. 23.—Bramah's hydraulic press.

31. **Hydraulic Elevator.** Another important application of the multiplication of force through the principle of equal

transmission of pressure by fluids is the hydraulic elevator, used as a means of conveyance from floor to floor in buildings. In its simplest form it consists of a cage A, supported on a piston P, which works in a long cylindrical tube C. (Fig. 24). The tube is connected with the water mains and the sewers by a three-way valve D which is actuated by a cord E passing through the cage. When the cord is pulled up by the operator, the valve takes the position shown at D, and the cage is forced up by the pressure on P of the water which rushes into C from the mains. When the cord is pulled down, the valve takes the position shown at F (below), and the cage descends by its own weight forcing the water out of C into the sewers.

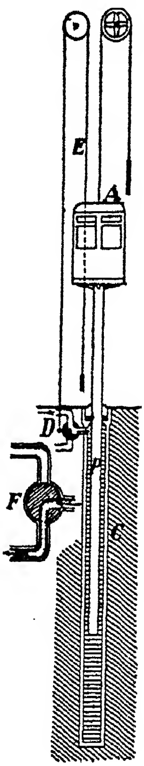


FIG. 24.—Hydraulic elevator.

The above is a very simple form of elevator. For higher lifts or increased speed and for safety many improvements have been added, but the elevators recently installed have been almost exclusively of the electric type.

32. Canal Lift-lock. The hydraulic lift-lock, designed to take the place of ordinary locks where a great difference of level is found in short distances, is another application of the principle of equal transmission. Fig. 25 gives a general view of the Peterborough Lift-lock, the largest of its kind in the world, and Fig. 26 is a simple diagrammatic section showing its principle of operation. The lift-lock consists of two immense hydraulic elevators, supporting on their pistons P_1 and P_2 tanks A and B in which float the vessels to be raised or lowered. The cylinders in which the pistons move are connected by a pipe containing a valve R which can be operated by the lockmaster in his cabin at the top of the

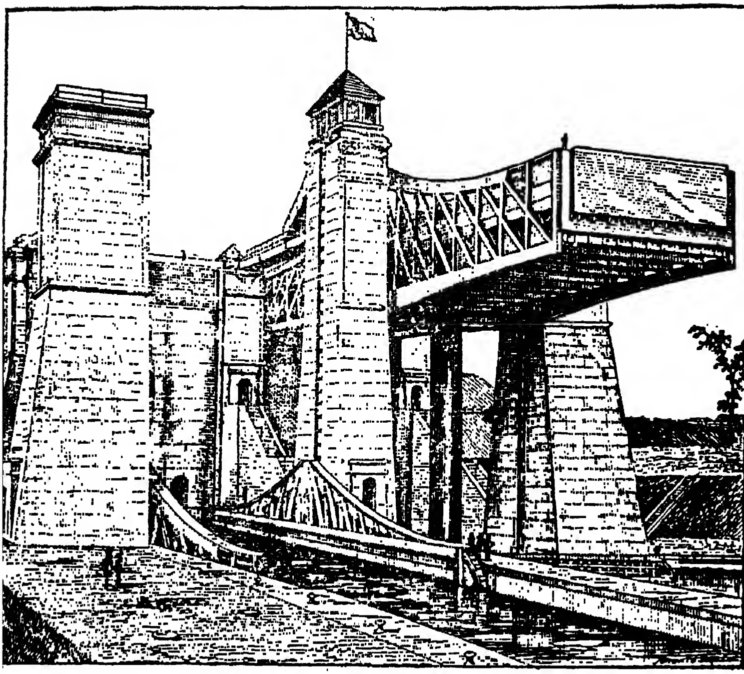


FIG. 25—Hydraulic lift-lock at Peterborough, Ont., capable of lifting a 140-foot steamer 65 feet.

central tower. To perform the lockage, the vessel is towed into one tank and the gates at the end leading from the canal are closed. The upper tank is then made to descend by being loaded with a few inches more of water than the lower. If now the valve is opened, the additional weight in the upper tank forces the water from its cylinder into the other, and it gradually descends while the other tank is raised. The action, it will be observed, is automatic, but machinery is provided for forcing water into the cylinders to replace that lost through leakage.

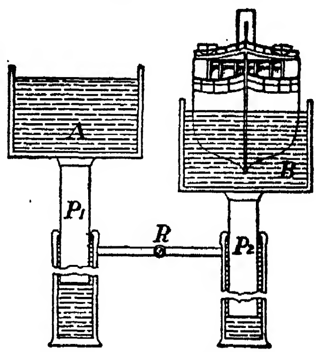


FIG. 26.—Principle of the lift-lock.

33. Hydraulic Brakes. Most of the newer motor cars are now equipped with hydraulic brakes. The main advantages of these over the older mechanical brakes are the simple flexible pipe connections to the wheels and the uniformity of the pressures exerted on the brake drums. The main working parts of such a system are shown, much simplified, in Fig. 27.

The master cylinder consists of the cylinder proper *A* and the supply tank *B* immediately above it. The function of the latter is to maintain a constant volume of the brake fluid in the system in spite of changes in temperature. When the pedal *C* is pressed the piston *D* moves to the right, closing the opening *E* and forcing fluid from the cylinder through the tubing *F* to the four wheel cylinders, one of which is shown in the diagram.

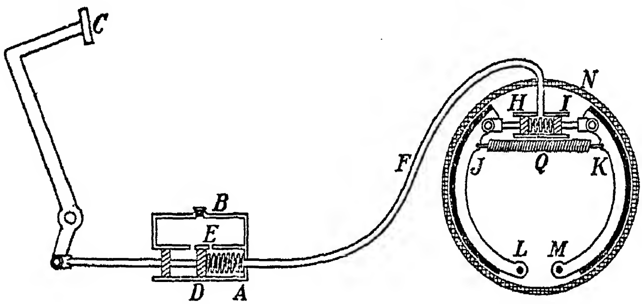


Fig. 27.—Simplified diagram of hydraulic brake system.

On the inner side of each wheel is a brake drum *N* which of course turns with the wheel. Within this drum is the wheel cylinder, which contains two pistons *H* and *I*, connected by links to the brake shoes *J* and *K*. These shoes are pivoted at *L* and *M*. The wheel cylinder and the brake shoe mechanism, including the pivots *L* and *M*, are rigidly attached to the brake support. In the case of the rear wheels, the wheel is securely fastened to the end of the axle and turns with it, while the brake support is attached to the sleeve or housing within which the axle turns. For the front wheels, the wheel turns on the end of the axle which is fixed and the brake support is attached to it.

When the liquid is forced into the wheel cylinder the pistons move outward, pushing the shoes J and K against the inner surface of the brake drum and stopping the car.

When the foot pedal is released the restoring spring Q returns the brake shoes and the pistons to their normal positions.

The liquid used in the hydraulic brakes of a motor car is not water, as its name would suggest, but a mixture of castor oil and ether, with other ingredients added to make it more stable.

PROBLEMS AND QUESTIONS

1. Why do the tires on an automobile tend to flatten at the bottom when the car is loaded heavily?

2. Name some advantages of the hydraulic elevator. Also some disadvantages.

3. Why is not water used in the motor car hydraulic brakes? Give several reasons.

4. A closed vessel is filled with liquid, and two circular pistons, whose diameters are respectively 2 cm. and 5 cm. inserted. If a force of 50 gm. is applied to the smaller piston, find the resulting force exerted on the larger piston.

5. The diameter of the large piston of a hydraulic press is 100 cm. and that of the smaller piston 5 cm. What force will be exerted by the press when a force of 2 kilograms is applied to the small piston?

6. The diameter of the piston of a hydraulic elevator is 14 inches. Neglecting friction, what load, including the weight of the cage, can be lifted when the pressure of the water in the mains is 75 pounds per sq. inch?

7. The diameter of the piston of a hydraulic elevator is 10 inches, and 400 pounds of the weight of the car is not counterpoised. What must be the pressure of the water if a weight of 500 pounds loaded in the car can be raised?

CHAPTER VI

LIQUIDS UNDER THEIR OWN WEIGHT

34. Relation between Pressure and Depth. In § 27 we have mentioned that a liquid exerts pressure on the sides and bottom of the containing vessel even when no external force is applied to the liquid. Every swimmer knows that a similar pressure is exerted on his body as soon as he dives below the surface of the water.

This pressure is due to the weight of the liquid; and, since the lower layers of the liquid have to support the upper layers, it is to be expected that the pressure within the mass of the liquid will increase with the depth. This may be investigated by the following experiment:

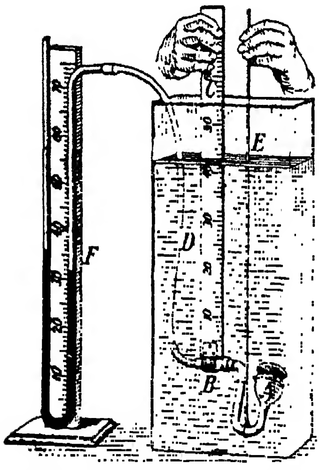


FIG. 28.—Apparatus to show that pressure is proportional to depth and is the same in all directions.

Prepare a pressure gauge of the form shown in Fig. 28 by stretching a rubber membrane over a thistle-tube *A*, which is connected by means of a rubber tube with a U-shaped glass tube *F*, partially filled with coloured water. The action of the gauge is shown by pressing on the membrane. The pressure is transmitted to the surface of the water in *F* by the air in the tube and is measured by the difference in level of the water in the branches of the U-tube.

Now place *A* in a jar of water (which should be at the temperature of the room), and gradually push it downward (Fig. 28). The changes in the level of the water in the branches of the U-tube indicate an increase in pressure with the increase in depth.

Careful experiments show that **this pressure increases from the surface downward in direct proportion to the depth.**

Now, by means of the wire *E*, turn the thistle-tube *A* in different directions, the centre of the membrane being kept all the time at the same depth, and observe the levels in the U-tube. They remain steady. Evidently the upward, downward and lateral pressures are equal at the same depth.

We find therefore that **the pressure is equal in all directions at the same depth.**

35. Magnitude of Pressure due to Weight. The downward pressure of a liquid, say water, on the bottom of a vessel with vertical sides is obviously the weight of the liquid. But if the sides of the vessel are not vertical, the magnitude of the force is not so apparent. Let us investigate this question experimentally, using the apparatus shown in Fig. 29.*

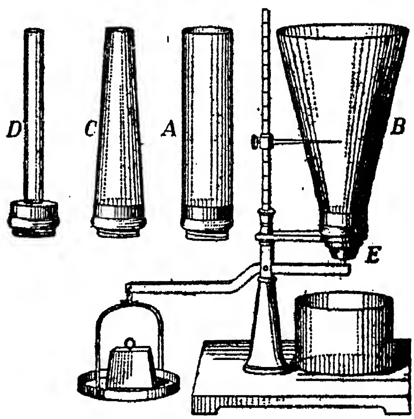


FIG. 29.—Pressure on the bottoms of vessels of different shapes and capacities.

A, *B*, *C*, and *D* are tubes of different shapes but made to fit into a common base. *E* is a movable bottom held in position by a lever *F* and weight. Attach the cylindrical tube to the base, and support the bottom *E* in position. Now place any suitable weight in the scale-pan and pour water into the tube until the pressure detaches the bottom. If the experiment be repeated, using in succession the tubes *A*, *B*, *C*, and *D*, and marking with the pointer the height of the water

*An alternative apparatus is illustrated in "Mechanics" by Merchant, Chant and Cline, p. 246.

when the bottom is detached, it will be found that the height is the same for all tubes, so long as the weight in the scale-pan remains unchanged.

The pressure on the bottom of a vessel filled with a given liquid is, therefore, dependent only on the depth. It is independent of the form of the vessel and of the amount of liquid which it contains.

36. Calculation of Pressure: Examples. 1. What is the pressure at a point, (*a*) 2 m. below, (*b*) 30 ft. below, the surface of water?

(*a*) Consider 1 sq. cm. of horizontal area at a depth of 2 m. Then the thrust upon this surface is equal to the weight of a vertical column of water standing upon it and reaching to the surface. Its volume = 200 c.c., and its weight = 200 gm. Hence the pressure = 200 gm. per sq. cm., and it is the same in all directions.

(*b*) Taking 1 sq. ft. of horizontal area at a depth of 30 ft., the volume of the vertical column upon this = 30 cu. ft., and its weight = 30 × 62·4 pd. = 1872 pd. Hence the pressure is 1872 pd. per sq. ft.

2. How high must the water in a reservoir be above the level of a tap in a house to produce a pressure at the tap of 60 pd. per sq. in. when the water in the system is at rest?

First Solution: From the table on the page opposite page 1 we find that

1 gal. = 10 lb. of water at 62° F. = 277·3 cu. in.

Hence 1 pound = wt. of 27·73 cu. in. of water,

and 60 pd. = wt. of 60 × 27·73 cu. in. of water.

But 60 × 27·73 cu. in. is the volume of a column of water whose cross-section area is 1 sq. in. and whose height is 60 × 27·73 in. or 138·65 ft.

Hence a pressure of 60 pd. per sq. in. is produced by a difference in level of 138·65 ft.

Second Solution: The given pressure = 60 pd. per sq. in. = 60 × 144 pd. per sq. ft. which = 8640 pd.

But 1 cu. ft. of water weighs 62·4 pd. at 4° C., from which the pressure at a depth of 1 ft = 62·4 pd. per sq. ft.

Hence the depth of the water to produce a pressure of 8640 pd. per sq. ft. = 8640 ÷ 62·4 ft. = 138·5 (approx.).

37. Surface of a Liquid in Connecting Tubes. If a liquid is poured into a series of connecting tubes (Fig. 30), it will rise to the same horizontal plane in all the tubes. The reason is apparent. Consider, for example, the tubes A and B. Let a and b be two points in the same horizontal plane. The liquid is at rest only on the condition that the pressure at a in the direction ab is equal to the pressure at b in the direction ba; but since the pressure at either of these points varies as its depth only, and is independent of the shape of the vessel, or of the quantity of the liquid in the tubes, the height of the liquid in A above a must be the same as the height in B above b.

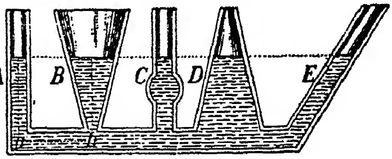


FIG. 30.—A liquid in connecting tubes rise to the same horizontal plane.

This principle, that "water seeks its own level," is in a variety of ways, of practical importance. Possibly the common method of supplying cities with water furnishes the

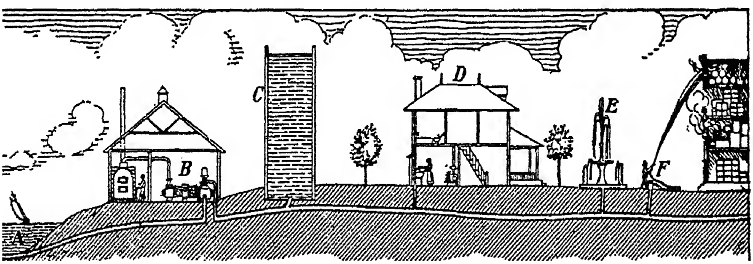


FIG. 31.—Water supply system. A, source of water supply; B, pumping station; C, standpipe; D, house supplied with water; E, fountain; F, hydrant for fire hose.

most striking example. Fig. 31 shows the main features of a modern system. While there are various means by which the water is collected and forced into a reservoir or standpipe, the distribution in all cases depends on the principle that, no matter how many branches of the service pipes there may

be, or whether they are high up or low down in the streets or buildings, the water in them tends to rise to the level of the water in the original source of supply connected with the pipes.

The water gauge shown in Fig. 32 is another useful application of the same principle. The height of the water in the glass tube on the outside of the boiler or tank is the same as that of the water inside and indicates when more water should be added.

FIG. 32.—A water gauge.

38. Artesian Wells. An artesian well is one made by boring until water is reached, sometimes at a great depth. Often the water rises to a height above that of the surrounding country. The rise of water in such wells is also due to

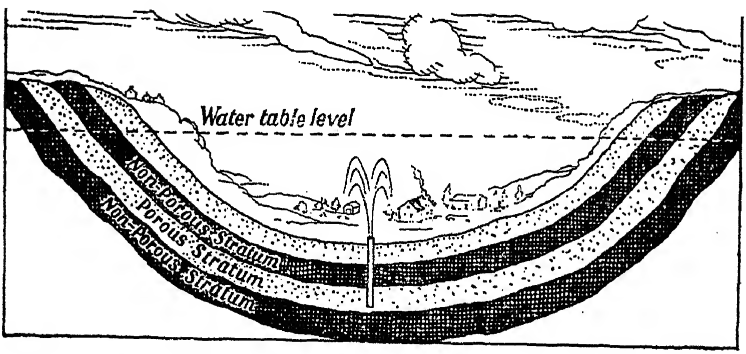


FIG. 33.—Artesian basin. The water collects in the porous stratum.

the tendency of a liquid to find its own level. These wells are bored at the bottom of cup-shaped basins (Fig. 33), which are frequently many miles in width. Between two non-porous strata is found a stratum of loose sand, gravel, or broken stone containing water which has run into it at the points where the porous stratum reaches the surface. When the upper non-porous stratum is pierced, the water tends to

rise with a force whose magnitude depends on the height of the water exerting the pressure.

PROBLEMS

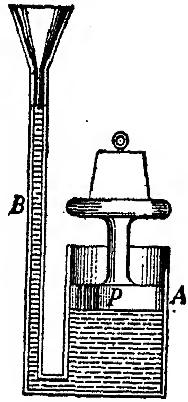


FIG. 34.

1. The area of the cross-section of the piston P (Fig. 34) is 120 sq. cm. What weight must be placed on it to maintain equilibrium when the water in the pipe B stands at a height of 3 metres above the height of the water in A?

2. The water pressure at a faucet in a house supplied with water by pipes connected with a distant reservoir is 80 pounds per sq. inch when the water in the system is at rest. What is the vertical height of the surface of the water in the reservoir above the faucet? (1 lb. water = 27·65 c. in. or 1 cu. ft. water = 62·5 lb.)

3. The area of the top of a cork in the neck of a bottle is $\frac{1}{2}$ sq. in., and to push it into the bottle a force of 20 pounds is required. At what depth in a lake will the pressure exerted by the water push the cork in?

4. The Pacific Ocean 145 mi. southeast of Tokio, Japan, is 5438 fathoms deep. Find the pressure on the ocean floor there. (1 fathom = 6 feet, and 1 cu. ft. of sea-water = 64 lb.)

5. Taking the surface area of a boy's body to be 12 sq. ft., find the total force on his body if he has dived to a depth of 8 ft. below the surface of a swimming pool. (Take 1 cu. ft. water = 62·5 lb.)

6. When the water pressure in the town's pipes is 75 pounds per sq. in., how high above the pipes is the water in the standpipe? (Fig. 31.)

CHAPTER VII

BUOYANCY OF LIQUIDS

39. Buoyant Force of a Liquid. We know very well that a liquid exerts an upward force upon a body which is either partially or completely immersed in it. A cork or a sea-gull bobs about on the surface of a lake, a heavy log floats on the river and is towed to the saw-mill, and even the great ship of fifty thousand tons is supported by the water. In all these cases the object floats; its weight is entirely overcome by the upward force due to the water.

But an upward force is exerted also when the body is fully immersed. An expert swimmer can keep a drowning person from sinking, though out of the water he might not be able to lift the body at all. Sometimes, in fishing from a boat a heavy stone is attached to a rope and let down as an anchor. On pulling it up, to go to another place, comparatively little effort is needed as long as the stone is in the water, but it becomes decidedly heavier as soon as it comes to the surface.

Let us find out by experiment just how much of a body's weight is apparently lost when it is immersed in a liquid.

40. The Principle of Archimedes. Take a metal cylinder *A*, (Fig. 35) closed at both ends, which fits exactly into a hollow socket *B*. Hook the cylinder to the bottom of the socket, suspend them from one end of the beam of a balance, and add weights to the other end to bring the balance to equilibrium. Next, surround *A* with water, as shown in the figure. The buoyancy of the water on *A* destroys the equilibrium. Now carefully pour water into the socket *B*. It will be found that when *B* is just filled, equilibrium is restored.

Hence the buoyant force of the water upon the cylinder is equal to the weight of the water displaced.

The apparatus shown in Fig. 35 is designed especially to demonstrate the law of buoyancy, but we can easily dispense with it.

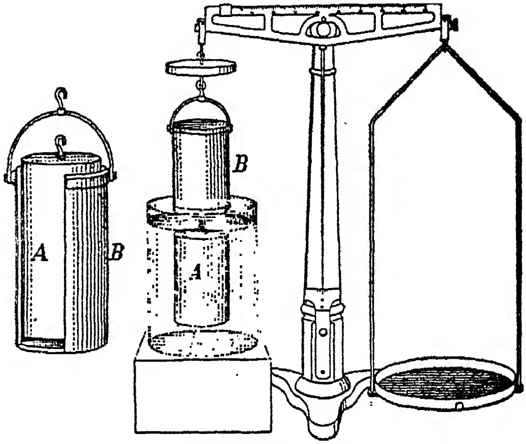


FIG. 35.—Determination of buoyant force.

By means of a fine thread suspend a heavy body, such as a stone or a piece of iron, from one end of a balance and find its weight. Let it be 158 grams. Then surround the body with water as in Fig. 36 and weigh again. Let the weight now be 137 grams. The buoyant force of the water is thus 158 − 137 = 21 grams. Next, lower the body into an overflow can (Fig. 14 on p. 19) and catch the overflow in a beaker or other vessel whose weight has been carefully determined. Weigh again and by subtraction find the weight of the water which has been displaced by the body. It will be found to be 21 grams.

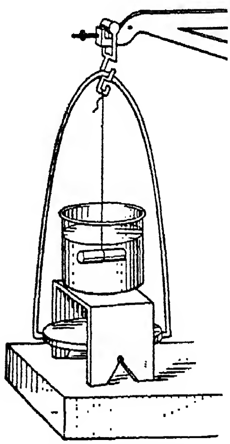


FIG. 36.—Finding the apparent loss in weight when a body is immersed in a liquid.

If an overflow can is not available, lower the body into the water in a graduate (see Fig. 16 on p. 20) and note the rise in the water. It will be found to be 21 c.c., the weight of which is 21 grams.

If we repeat the experiment with the body immersed in gasoline the buoyant force will be found equal to the weight of the gasoline displaced.

We therefore conclude:

The buoyant force exerted by a liquid upon a body immersed in it is equal to the weight of the liquid displaced by the body; or, in slightly different words,

A body when weighed in a liquid loses in apparent weight an amount equal to the weight of the liquid which it displaces.

This is known as the **Principle of Archimedes***.

Archimedes had been asked by Hiero to determine whether a crown which had been made for him was of pure gold or alloyed with silver. It is said that the action of the water when in a bath suggested to him the principle of buoyancy as the key to the solution of the problem. The story is that he leaped from his bath, and rushed through the streets of Syracuse, (in Sicily) crying "Eureka! Eureka!" (I have found it, I have found it.)

41. Theoretical Proof by Calculation. Archimedes' principle is so important that a simple proof by calculation will be given. Consider a solid in the form of a cube to be immersed in water with its upper face horizontal (Fig. 37).

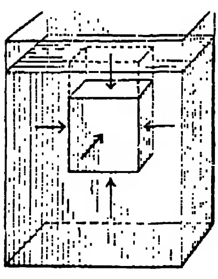


Fig. 37.—Buoyant force of a liquid on a solid.

Let the edge of the cube be 3 cm. in length and the upper face be 2 cm. below the surface.

Evidently the thrusts on the vertical sides balance, and the resultant vertical force due to the water will be equal to the difference between the thrusts on the bottom and the top.

Now the thrust on the top is equal to the weight of a column of water standing on 9 sq. cm. and reaching to the

*The law holds for gases as well as for liquids.

surface, that is, having a height of 2 cm. The volume is 18 c.c. and the weight is 18 grams.

The thrust on the bottom (upward) is equal to the weight of a column of water standing on 9 sq. cm. and reaching to the surface, that is, having a height of 5 c.m. The volume is 45 c.c. and the weight is 45 grams.

Resultant thrust = 45 − 18 = 27 grams (upward.)

But the volume of the cube is 27 c.c. and the weight of the water displaced = 27 grams.

Next let us place the cube at the same depth below the surface of a liquid whose specific gravity is 2. The downward thrust on the top will now be 36 grams and the upward thrust on the bottom 90 grams.

Hence the buoyant force = 90 − 36 = 54 grams. But the weight of the liquid displaced is also 54 grams.

It is clear then that the buoyant force is always equal to the weight of the liquid displaced.

42. Principle of Flotation. It is obvious that if the weight of a body *immersed* in a liquid is greater than the weight of the liquid displaced by it, the body will sink; but if less, the body will rise until it reaches the surface. Here it will come to rest when it has risen so much above the surface that the weight of the liquid then displaced is equal to the weight of the body.

The weight of a floating body is equal to the weight of the liquid which it displaces when floating. For example, consider again the cube referred to in Fig. 37. If its weight is less than 27 grams, say 18 grams, it will float in water. In this case the downward thrust on the top has disappeared and the weight of the cube is supported by the thrust on the bottom, which equals the weight of a column of water 9 sq. cm. in section and 2 cm. deep.

The principle of flotation may be demonstrated with the overflow can. Place it on one pan of a balance and fill it to overflowing with water (Fig. 37a), and then put weights on the other pan until equilibrium is obtained. Now float a block of wood on the water and collect the overflow in the catch bucket. When the overflow has ceased it will be seen that the balance is in equilibrium again. This shows that the water displaced by the block is equal to the weight of the block.

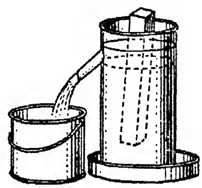


Fig. 37a.—Floating a block of wood in an overflow can.

Around the hull of a ship is painted the "load line", and the ship is fully loaded when this line is at the surface of the water. By calculating the volume of the water then displaced we can deduce its weight and hence the total weight of the ship. This is the *displacement* of the ship. In the case of the *Queen Mary* it is about 73,000 tons (each of 2240 lb.)

PROBLEMS AND QUESTIONS

(Take 1 c. ft. water = 62·5 lb.)

1. A cubic foot of marble which weighs 160 pounds is immersed in water. Find (1) the buoyant force of the water on it, (2) the weight of the marble in water.

2. Twelve cubic inches of a metal weigh 5 pounds in air. What is the weight when immersed in water?

3. If 3,500 c.c. of a substance weigh 6 kg., what is the weight when immersed in water?

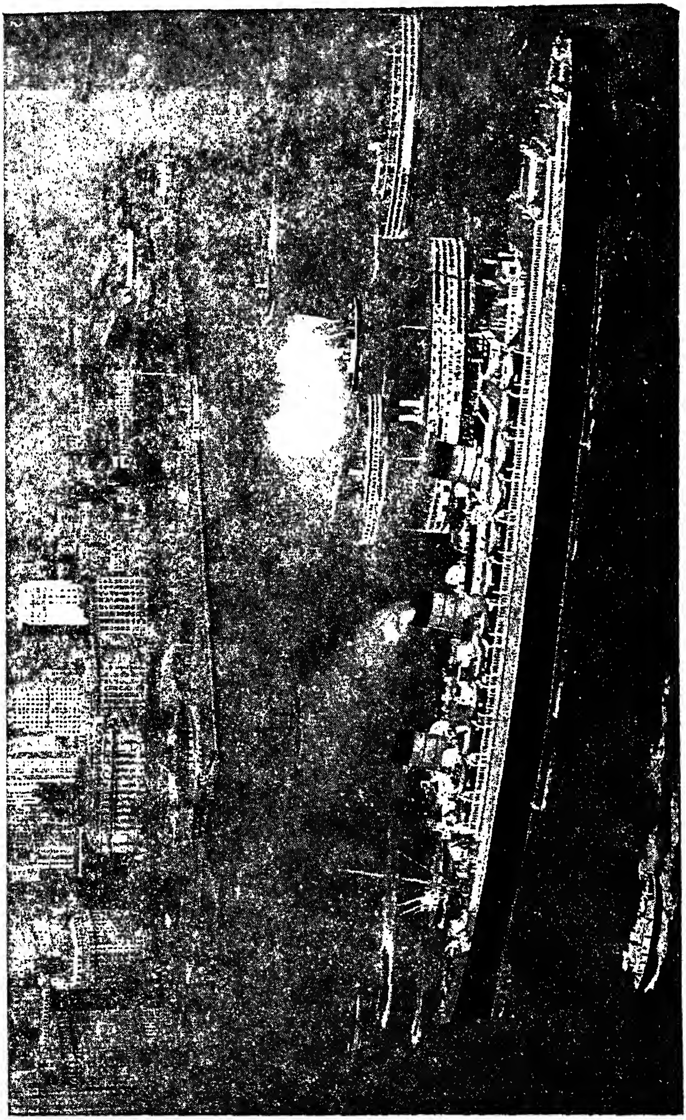
4. A piece of aluminium whose volume is 6·8 c.c. weighs 18·5 grams. Find the weight when immersed in a liquid twice as heavy as water.

5. If a body has a weight of 150 grams and a volume of 20 c.c., what portion of its weight will it lose if immersed in water?

6. One cubic decimetre of wood floats with $\frac{3}{5}$ of its volume immersed in water. What is the weight of the cube?

7. A cubic centimetre of cork weighs 250 mg. What part of its volume will be immersed if it is allowed to float in water?

8. The cross-section of a boat at the water-line is 150 sq. ft. What additional load will sink it 2 inches?



THE "QUEEN MARY" ARRIVING AT NEW YORK ON HER FIRST TRIP JUNE 1 1936

● Plate 3

This gigantic liner is 1018 feet in length and 118 feet in breadth. Her turbine engines operate four propellers and develop 200,000 horse-power. Her displacement is about 73,000 tons and her speed 30 knots, or 35 ordinary miles per hour.

Aerial Explorations, Inc., N.Y.C.)

9. A scow with vertical sides is 25 feet long and 12 feet wide, and it sinks $2\frac{1}{2}$ inches when a team of horses walks on it. Find the weight of the team.

10. What is the least force which must be applied to a cu. ft. of elm, which weighs 35 lb. per cu. ft., that it may be wholly immersed in water?

11. A piece of wood whose mass is 100 grams floats in water with $\frac{3}{4}$ of its volume immersed. What is its volume?

12. A piece of wood weighing 100 pounds floats in water with $\frac{2}{3}$ of its volume above the surface. Find its volume.

13. Why will an iron ship float on water, while a piece of the iron of which it is made sinks?

14. A vessel of water is on one scale-pan of a balance and counterpoised. Will the equilibrium be disturbed if a person dips his fingers into the water without touching the sides of the vessel? Explain.

15. A piece of coal is placed in one scale-pan of a balance and iron weights are placed in the other scale-pan to balance it. How would the equilibrium be affected if the balance, coal and weights were now placed under water? Why?

16. Why can a stout person usually float more easily than a thin person?

17. Referring to Fig. 26, answer the following question: If the depth of the water in the tank A is the same as that in the tank B which contains the vessel, which tank will be the heavier?

18. A fish can rise or sink in water as it wishes. How does it produce this effect? If dead it floats; why?

19. Will there be any change in the depth to which a ship sinks as it comes from the Atlantic Ocean into Lake Ontario? Explain.

20. The Royal Society of London was instituted during the reign of Charles II. It is said that at one of its meetings the king proposed the following question:—Suppose two vessels are placed on the pans of a balance and water is poured in until they exactly balance. If now a fish is put into one, why is the balance not destroyed? What is your answer to this question? King Charles II was called "The Merry Monarch".

CHAPTER VIII

SPECIFIC GRAVITY

43. Specific Gravity of a Solid Heavier than Water One method of determining the specific gravity of a solid body has already been discussed in § 23. It can also be found by applying Archimedes' principle.

Suppose we wish to find the specific gravity of a piece of iron. First, suspend it from one end of a balance by means of a fine thread and find its weight in air. Let it be 263·5 grams. Then bring a vessel containing water under the body and raise it until the body is fully immersed (Fig. 36, § 40). Let the weight now be 226·4.

We may arrange our calculations thus:

Weight of the iron in air $= 263{\cdot}5$ gm.

Weight of the iron in water $= 226{\cdot}4$ gm.

Loss of weight in water $= 263{\cdot}5 - 226{\cdot}4 = 37{\cdot}1$ gm.
$=$ wt. of equal vol. of water.

$$\text{But specific gravity} = \frac{\text{Weight of body}}{\text{Weight of an equal vol. of water}}$$

$$\text{Hence the S. G. of the iron } \frac{263{\cdot}5}{37{\cdot}1} = 7{\cdot}10.$$

Also, the density of the iron $= 7{\cdot}10$ gm. per c.c.

In general terms, if a body weighs a grams in air and b grams in water,

$$\begin{aligned} \text{then } (a-b) \text{ grams} &= \text{loss of weight in water} \\ &= \text{weight of an equal vol. of water,} \\ \text{and S. G.} &= \frac{a}{a-b}. \end{aligned}$$

This also expresses the density in grams per c.c.

44. Specific Gravity of a Solid Lighter than Water. Select a heavy body which will cause the light body to sink in the water when attached to it, and proceed as follows:

Let the body be a small wooden block. (Fig. 37 *b*).

1. Weigh it in air; let the weight = 10 gm.

2. Attach the sinker *S*. Weigh block and sinker with sinker only in the water. Let the weight = 30 gm.

3. Weigh again when both are in the water. Let the weight = 5 grams.

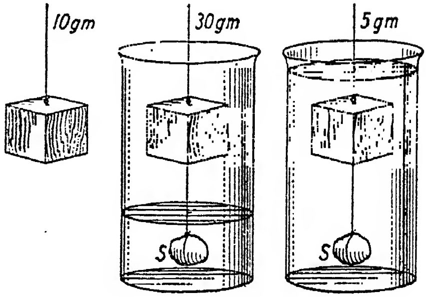


Fig. 37*b*—Finding the S.G. of a block of wood.

Now the only difference between the second and third operations is that in the former the body is weighed in the air, in the latter in the water. The sinker is in the water in both cases.

Hence, (30 − 5) gm. = the buoyancy of the water on the wood, and this = the weight of the water displaced by the wood.

$$\text{Then the S. G.} = \frac{10}{30 - 5} = 0{\cdot}4.$$

45. Specific Gravity of a Liquid by Archimedes' Principle. In order to find the specific gravity of a liquid (gasoline, for example) by Archimedes' principle take a heavy body (say, a glass stopper) and weigh it in air, then when immersed in water and finally when immersed in the liquid.

We may make our record thus:

Weight of the glass stopper in air	=	100 gm.
" " " " " water	=	60 gm.
" " " " gasoline	=	70 gm.

Then weight of water displaced by stopper = 100 − 60 = 40 gm.
and " " gasoline " " " = 100 − 70 = 30 "

Thus equal volumes of water and gasoline weigh respectively 40 gm. and 30 gm.

$$\text{Hence, S. G. of the gasoline} = \frac{30}{40} = 0{\cdot}75.$$

Question.—What is the density of the gasoline?

Problem.—If a glass stopper weighs a grams in air, b grams in water and c grams in a liquid whose specific gravity is to be determined, show that

$$\text{S.G. of the liquid} = \frac{a-c}{a-b}.$$

46. The Hydrometer. The approximate specific gravity of a liquid is a quantity which it is often necessary to determine quickly and for this purpose an instrument known as a *hydrometer* has been devised. The principle underlying its action may be illustrated as follows.

Take a straight rod of wood, of cross-section 1 sq. cm. and (say) 25 cm. long, and bore a hole in one end. After inserting enough shot to make the rod float upright in water, plug up the hole. After this, mark on one of the long faces a centimetre scale, and dip the rod in hot paraffin to render it impervious to water.

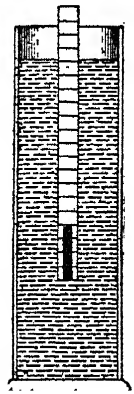


FIG. 38.—Illustration of the principle of the hydrometer.

Now place the rod in water (Fig. 38) and suppose it to sink to a depth of 16 cm. Then the weight of the rod = weight of water displaced = 16 gm.

Again, suppose it to sink to a depth of 12 cm. in a liquid whose specific gravity is to be determined.

Then, since the weight of liquid displaced equals the weight of the rod,

12 c.c. of the liquid weigh 16 gm.

And density of the liquid $= \frac{16}{12}$ gm. per c.c.,

Whence, the S. G. of the liquid $= \frac{16}{12} = 1 \cdot 33$.

$$\text{Or, the S. G. of the liquid} = \frac{\text{vol. of water displaced by hydrometer}}{\text{vol. of the liquid displaced by hydrometer}}.$$

It is evident, also, that the rod could be marked so as to indicate the specific gravity directly. Thus, for readings 12, 16, 20 cm., the S.G. is 1·33, 1·00, 0·80 respectively.

For commercial purposes the hydrometer is usually constructed in the form shown in Fig. 39. At the end of a slender stem B is a float A, and a little bulb C which contains mercury and makes the instrument take an upright position when in a liquid. The graduations are either on the outside of the stem or on a paper within it.

The weight and volume are so adjusted that the instrument sinks to the division mark at the lower end of the stem in the densest liquid to be investigated and to the division mark in the upper end in the least dense liquid.

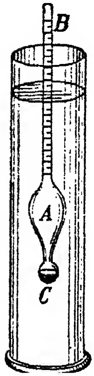


Fig. 39.—The hydrometer

The scale on the stem indicates directly the specific gravities of liquids between these limits. The float *A* is usually made much larger than the stem to give sensitiveness to the instrument.

As the range of an instrument of this class is necessarily limited, special instruments are constructed for use with different liquids. For example, one instrument is used for milk, another for the acid in a storage battery and so on. That for testing a storage battery is illustrated in Fig. 40. The lower end is thrust into the battery and, by pressing the rubber bulb and letting it go, enough acid is drawn into the tube to float the hydrometer. The depth to which it sinks shows the general condition of the liquid in the battery.

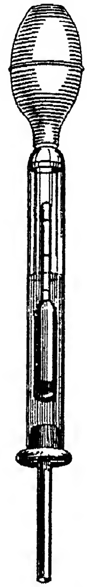


Fig. 40. — Storage battery hydrometer.

A hydrometer for testing "anti-freeze" liquids is shown in Fig. 40a. It is similar to that last described, and its object is to determine how low the temperature may fall and the anti-freeze still protect the automobile engine.

The stronger an anti-freeze solution is, the lower its temperature may fall before it freezes and ceases to circulate in the cooling system of the engine; and by experiment one can find the freezing point of any solution. Thus a 40 – 60 glycerine solution (i.e., 40 parts by weight of glycerine to 60 of water) freezes at 1° F.; a 45–55 mixture at –15° F.; a 50–50 mixture at –25° F.; and so on.

Each of these mixtures has its own specific gravity, which depends not only on the amount of the solute in the solution but also on the temperature of the solution when tested.

Tables have been prepared from which one may read the freezing-point of a solution and hence its strength if one knows its temperature and specific gravity. These tables are engraved on a metal collar around the tube just below the hydrometer h, and each kind of anti-freeze requires its own set of tables.

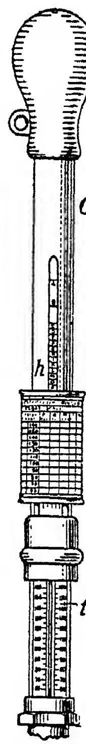


FIG. 40a.—An anti-freeze tester.

In practice a sample of the anti-freeze is drawn from the radiator of the car into the tube C; its temperature is given by the thermometer t and its specific gravity by the hydrometer h. From the collar one finds the freezing-point and hence the strength of the solution which determines whether more of the solute or additional water is required.

PROBLEMS

1. A piece of metal whose mass is 120 gm. weighs 100 gm. in water and 104 gm. in alcohol. Find the volume and specific gravity of the metal, and the specific gravity of the alcohol.

2. A mass of lead is suspected of being hollow. It weighs 2486 gm. in air and 2246 gm. in water. What is the volume of the cavity? (S. G. of lead, 11·3.)

3. A body whose mass is 12 gm. has a sinker attached to it, and the two together displace when submerged 60 c.c. of water. The sinker alone displaces 12 c.c. What is the specific gravity of the body?

4. A body whose mass is 6 gm. has a sinker attached to it, and the two together weigh 16 gm. in water. The sinker alone weighs 24 gm. in water. What is the specific gravity of the body?

5. If a body when floating in water displaces 12 c.c., what is the density of a liquid in which when floating it displaces 18 c.c.?

6. A uniform wooden rod 5 cm. square and 30 cm. long is loaded so that it floats upright in water with 20 cm. below the surface. If the rod were placed in alcohol (specific gravity 0·8) what length of the rod would be below the surface?

7. A cylinder of wood 8 cm. long floats vertically in water with 5 cm. submerged. (*a*) What is the specific gravity of the wood? (*b*) What is the specific gravity of the liquid in which it will float with 6 cm. submerged? (*c*) To what depth will it sink in gasoline whose specific gravity is 0·75?

8. A hydrometer floats with $\frac{2}{3}$ of its volume submerged when floating in water, and $\frac{3}{4}$ of its volume submerged when floating in another liquid. What is the specific gravity of the other liquid?

REVIEW QUESTIONS

1. State Pascal's Law, and name three practical applications of it.

2. State three laws regarding the pressure in a liquid at rest.

3. A stone is tied to a cubical tin box 10 cm. to the edge and it is sunk in the ocean. It is able to withstand a pressure of 20 kg. per sq. cm. How far down will it sink before being crushed? At that time what will be the total force on a side? What is the measure of the pressure in pounds per sq. cm.? (Take sp. gr. of sea-water as 1.02).

4. Explain the action of an artesian well. Why does the water in some such wells shoot far up into the air?

5. State the Principle of Archimedes. How would you verify it experimentally?

6. State the principle of flotation, and give some of the greatest illustrations of it.

7. Distinguish between density and specific gravity, and illustrate by giving the density and the specific gravity of iron.

8. You wish to find the specific gravity of mercury by means of a specific gravity bottle, but the mercury at your disposal will not fill it. How would you proceed?

9. Describe a hydrometer suitable for testing a storage battery.

CHAPTER IX

PRESSURE OF THE AIR

47. Has Air Weight? This question puzzled investigators from the time of Plato and Aristotle down to the seventeenth century, when it was answered by Galileo and Guericke.

Galileo (1564-1642) convinced himself that air had weight, by proving that a glass globe filled with air under high pressure weighed more than the same globe when filled with air under ordinary conditions. Guericke (1602-1686), the inventor of the air-pump, showed that a copper globe weighed more when filled with air than when exhausted.

The experiments of Galileo and Guericke may be repeated with a glass flask fitted with a tap (Fig. 41). If the flask is weighed when filled with air under ordinary pressure, then weighed when the air has been compressed* into it with a bicycle pump, and again when the air has been exhausted from it with an air-pump, it is found that the first weight is less than the second but greater than the third.

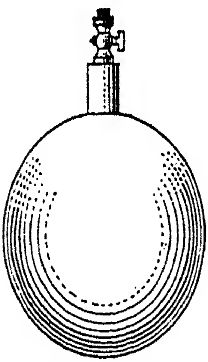


FIG. 41.—Globe for weighing air.

By subtracting the weight of the exhausted globe from its weight when filled with air under atmospheric pressure, the weight of the air removed may be obtained. Then the tap may be opened under water and the volume of the air removed found by measuring in a graduate the water which enters. From these figures the approximate weight of a litre of air may be calculated.

*The pressure should not be increased very much because the flask may burst.

Since the volume of a mass of air varies with changes in temperature and pressure, the weight of a certain volume will be constant only at a fixed temperature and pressure.

Exact quantitative experiments have shown that the mass of a litre of air at 0° C. and under normal pressure of the air at sea-level (760 mm. of mercury) is 1·293 grams.

48. Weight of Air (Alternative Experiment). The simple apparatus shown in Fig. 42 may be used to find the weight of a litre of air.

Place about half an inch of water in the florence flask *A*, which should have a capacity of at least 300 c.c. Then insert firmly in the neck of the flask the rubber stopper, through which passes a short piece of glass tubing with a short rubber tube attached to it. Heat the water and let it boil for about two minutes, to ensure that the air has been driven out by the steam.

Next tighten the clamp *B* on the rubber tube and immediately remove the flame. As soon as the flask is cool enough weigh it, and then loosen the clamp to allow air to enter. Weigh again when you are sure that the air inside is at room temperature.

Using a graduate, find the volume of water needed to fill the flask. This will be the volume of the air which entered when the clamp was loosened.

Subtract the two weights, to find the weight of the air, and calculate the weight of one litre of air under the conditions of temperature and pressure at which the experiment was performed.

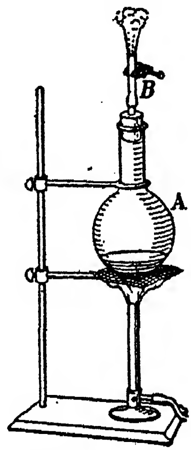


Fig. 42.—Finding the weight of air.

Example.—In making the following measurements a good balance is required.

Weight of flask after heating	= 255·62 gm.	(1)
Weight after air is admitted	= 256·13 "	(2)
Weight after being filled up with water	= 660·82 "	(3)
Hence, weight of air admitted, (2) − (1)	= 0·49 "	
and also weight of water poured in, (3) − (1)	= 405·20 "	
and hence volume of air admitted	= 405·20 c.c.	

From which 405·20 c.c. of air weigh 0·49 gm., and 1000 c.c. or 1 litre weighs 1·21 gm. (nearly).

It will be noticed that the weight of the air used is small and a slight error in weighing it makes a considerable difference in the final result.

PROBLEMS

1. Find the weight of the air in a class-room measuring $10 \times 8 \times 4$ metres in kilograms and in pounds. (Assume that 1 litre of the air weighs 1·293 gm.)

2. A flask weighed 280·64 gm. when empty, 284·19 gm. when filled with air and 3060·00 gm. when filled with water. Find the weight of 1 litre of air.

3. A cylindrical compressed air tank is 1 metre long and 28 cm. in diameter. The temperature of the air is 0° C. and the pressure gauge shows that the density of the air is ten times that of air at normal atmospheric pressure. Find the weight of the air in the tank.

4. Assuming that 1 l. of air weighs 1·293 gm., also that 1 cu. ft. = 28, 317 c.c. and 1 lb. av. = 453·59 gm. (see Table on page opposite page 1), show that 1 cu. ft. air weighs 0·0807 lb. av., and 1 lb. air occupies 12·39 cu. ft.

5. Find the weight in pounds av. of the air in a public hall measuring $40 \times 60 \times 20$ ft. (1 cu. ft. of air weighs 0·0807 lb.)

49. Pressure of Air. It is evident that, since air has weight, it must, like liquids, exert pressure upon all bodies with which it is in contact. Just as the bed of the ocean sustains enormous pressure from the weight of the water resting on it, so the surface of the earth, the bottom of the aerial ocean in which we live, is subject to a pressure due to the weight of the air supported by it. This pressure will, of course, vary with the depth. Thus the pressure of the atmosphere at Victoria, B.C., on the sea-level is greater than at points on the mountains to the east.

The pressure of the air may be shown by many simple experiments. The following are three examples:

1. Tie a piece of thin sheet rubber over the mouth of a thistle-tube (Fig. 43) and exhaust the air from the bulb by suction or by connecting it with the air pump. As the air is exhausted, the rubber is pushed inward by the pressure of the outside air.

2. Boil water vigorously in a tin can, and when the steam is coming off freely, push into it a good rubber stopper

and remove the heat. Throw cold water on it, or simply let it stand, and watch the result. (Fig. 44).

3. Thrust one end of a straw or a tube into water and withdraw the air from it by suction; the water is forced up into

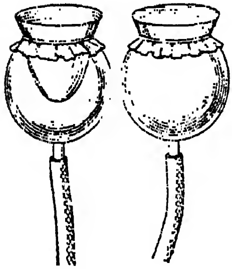
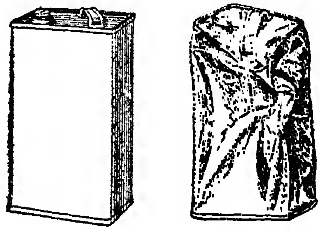


FIG. 43.—Rubber membrane forced inward by pressure of the air.



(a) (b)

FIG. 44.—Tin can (a) before cooling, (b) after cooling.

the tube. This phenomenon was known for ages, but it did not receive a satisfactory explanation until the facts of the weight and pressure of the atmosphere were established. It was previously explained on the principle that Nature had a horror for empty space.

The attention of Galileo was called to this problem in 1640 by his patron, the Grand Duke of Tuscany, who had found that water could not be lifted more than 32 feet by a suction pump. Galileo inferred that "resistance to vacuum" as a force had its limitations and could be measured; but although he had, as we have seen, proved that air has weight, he did not see the connection between the facts. After his death the problem was solved by his pupil, Torricelli, who showed definitely that the resistance to a vacuum was the result of the pressure of the atmosphere due to its weight.

QUESTIONS AND EXERCISES

1. Fill a tumbler and hold it inverted in a dish of water as shown in Fig. 45. Why does the water not run out of the tumbler into the dish?

2. Fill a bottle with water and place a sheet of writing paper over its mouth. Now, holding the paper in position with the palm of the hand, invert the bottle. (Fig. 46.) Why does the water remain in the bottle when the hand is removed from the paper?

3. Boil water in a flask A arranged as in Fig. 47, conducting the steam through the tube B into cold water C. Remove the heat. Observe and explain what happens. Next remove the tube D, plugging the hole in the cork through which it passes. Repeat the experiment and explain what happens.

4. Explain the action of a medicine dropper. (See Fig. 195, p. 180).

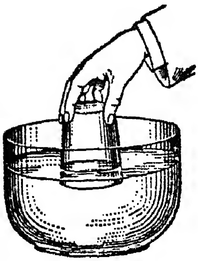


FIG. 45.

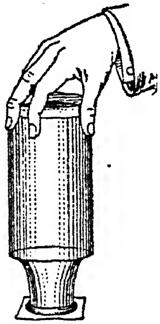


FIG. 46

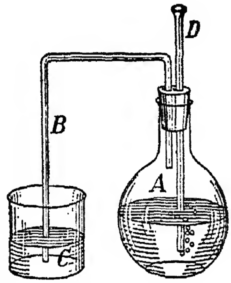


FIG. 47.

5. Why must an opening be made in the upper part of a vessel filled with a liquid to secure a proper flow at a faucet inserted at the bottom?

Can the water be emptied from a flexible rubber bag if the bag has a single small opening in it?

6. Fill a narrow-necked bottle with water and hold it mouth downward. Explain the action of the water.

7. On the tin top upon a pot of jam is sometimes seen the instruction:—"To open, puncture and push up at edge." Why puncture it?

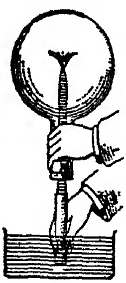


FIG. 48.

FIG. 49.

8. Arrange apparatus as shown in Fig. 48. By suction remove a portion of the air from the flask, and, keeping the rubber tube closed by pressure, place the open end in a dish of water. Now open the tube. Explain the action of the water.

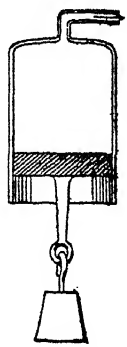


FIG. 50.

9. Guericke took a pair of hemispherical cups (Fig. 49) about 1·2 ft. in diameter, so constructed that they formed a hollow air-tight sphere when their lips were placed in contact, and, at a test at Regensburg before the Emperor Ferdinand III

and the Reichstag in 1654, showed that it required sixteen horses (four pairs on each hemisphere), to pull the hemispheres apart when the air was exhausted by his air-pump. Account for this.

10. If an air-tight piston is inserted into a cylindrical vessel and the air exhausted through the tube (Fig. 50), a heavy weight may be lifted as the piston rises. Explain this action. The apparatus shown in Fig. 22 in § 29 may be used for this experiment.

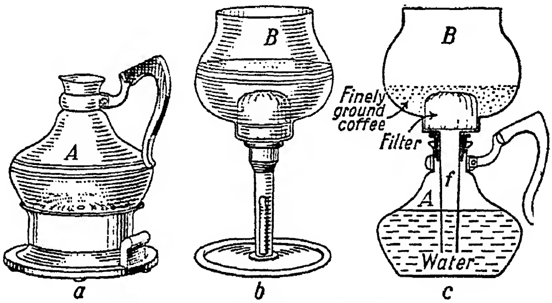


FIG. 51.—A utensil for making coffee.

11. A special type of coffee-maker is illustrated in Fig. 51. It consists of two parts, a vessel A and a funnel B, shown separately in a and b. They are made of heat-resisting glass. At the bottom of B is a ball of glass covered with filter cloth. Water is placed in A and B is put into A, fitting air-tight at the neck. Finely ground coffee is put in B and the utensil, as shown in c, is placed on a heater. It is observed that when the water becomes heated and steam is coming from the surface, the water goes up f, the stem of the funnel, mixing with and covering the ground coffee. The utensil is then removed from the heater, and after a while the liquid coffee comes down f into the vessel A, leaving the grounds behind. Then B is removed and placed on its stand and the coffee is served from A. Explain (a) why the water went from A up into B; and (b) why it came down again.

CHAPTER X

MEASURING THE PRESSURE OF THE ATMOSPHERE

50. The Torricellian Experiment. Torricelli concluded that, since water rises to a height of approximately 32 feet in a suction pump, and since mercury is about 14 times as heavy as water, the corresponding mercury column should be $\frac{1}{14}$ as long as the water column. To confirm his inference an experiment similar to the following was performed under his direction.

Take a glass tube about one metre long (Fig. 52), closed at one end, and fill it with mercury. Stopping the open end with the finger, invert it and place it in a vertical position, with the open end under the surface of the mercury in another vessel. Remove the finger. The mercury will fall a short distance in the tube, and after oscillating will come to rest with the surface of the mercury in the tube between 28 and 30 inches above the surface of the mercury in the outer vessel.

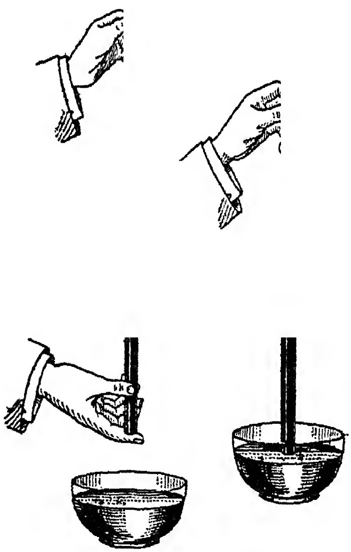


FIG. 52.—Mercury column sustained by the pressure of the air.

Torricelli concluded rightly that the column of mercury was sustained by the pressure of the air on the surface of the mercury in the outer vessel. This conclusion was confirmed by Pascal (1623-1662) who showed that the length of the mercury column varied with the

altitude. He asked his brother-in-law, Périer, who resided in the south of France, to test it on the Puy de Dôme, a near-by mountain over 1,000 yards high. Périer filled a tube about 4 ft. long with mercury, inverted it in a vessel containing mercury and carried it to the summit. The mercury column fell more than 3 in. This result pleased them very much.

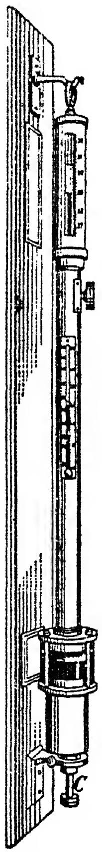


Fig. 53. — The cistern barometer

51. Barometer. Torricelli pointed out that the object of his experiment was "not simply to produce a vacuum, but to make an instrument which shows the mutations of the air, now heavier and dense, now lighter and thin."* The modern mercury barometer designed for this purpose is the same in principle as that constructed by Torricelli. With this instrument the pressure of the atmosphere is measured by the pressure exerted by the column of mercury which balances it, and changes in pressure are indicated by corresponding changes in the height of the mercury column.

Two forms of the instrument are in common use.

52. Cistern Barometer. This is simply a convenient arrangement of the original Torricellian experiment. The bowl, or cistern, and the tube are permanently mounted on a board, and a scale, engraved on the metal case protecting the glass tube, shows the height of the mercury in the tube above the surface of the mercury in the cistern.

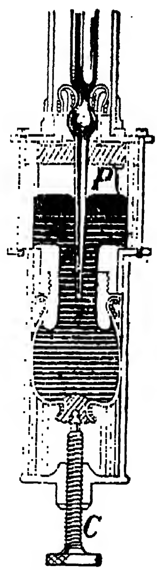


Fig. 53a.–Section of the cistern.

*Extract from a letter written by Torricelli, in 1644, to M. A. Ricci, in Rome, first published in 1663.

A well-known form of this instrument is shown in Figs. 53, 53a. The cistern has a flexible leather bottom which can be moved up or down by turning the screw *C*. Before taking the reading, the screw is turned until the surface of the mercury just touches the tip of the pointer *P*, which is the zero of the scale on the case. The height of the mercury is then read directly from the scale on the case. A vernier* is usually employed to determine the reading with exactness.

53. Siphon Barometer. This barometer consists of a tube of the proper length closed at one end and bent into U-shape at the other. (Fig. 54.) When filled and placed upright, the mercury in the longer branch is supported by the pressure of the air on the surface of the mercury in the shorter. A scale is attached to each branch. The upper scale gives the height of the mercury in the closed branch above a fixed point, and the lower scale the distance of the mercury in the open branch below the same fixed point. The sum of the two readings is the height of the barometer column.

Fig. 54.—Siphon barometer.

54. Aneroid Barometer. As its name implies,† this is a barometer constructed without liquid. (Figs. 55, 56.) In this form the air presses against the flexible corrugated cover of a circular, air-tight, metal box *A*, from which the air is partially exhausted. The cover, which is usually supported by a spring *S*, responds to the pressure of the atmosphere, being forced in when the pressure is increased, and springing out when it is decreased. The movement of the cover is very small, but it is multiplied and transmitted to an index hand *B* by a system of delicate levers and a

*An explanation of the vernier is given in the *Laboratory Manual* designed to accompany this book.
†Greek *a* = not, *neros* = wet.

chain or by gears. The slack of the chain is taken up by a spiral spring shown at the centre of the diagram in Fig. 55. The circular scale is graduated by comparison with a mercury barometer.

The aneroid is not so accurate as the mercury barometer, but it is portable and sensitive and is in very common use. It is

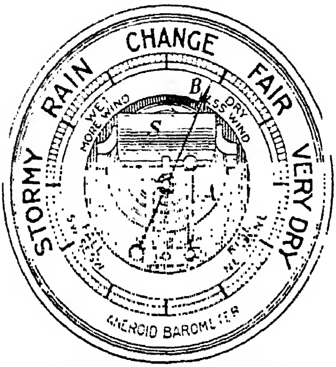


FIG. 55.—Aneroid barometer.

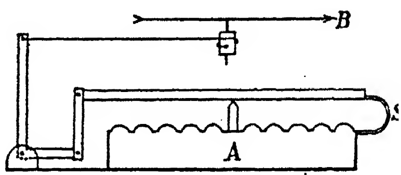


FIG. 56.—Simplified diagram of aneroid barometer.

mining differences of level. A good aneroid will indicate a fall in pressure in going from the cellar to the attic of a house.

55. Variations in Atmospheric Pressure. By continually observing the height of the barometer at any place we learn that the atmospheric pressure is constantly changing. Sometimes a decided change takes place within an hour.

Again, by comparing the simultaneous readings of barometers distributed over a large stretch of country we find that the pressure is different at different places.

On the face of an aneroid barometer is often seen the words, "stormy, rain, change, fair, very dry." They have little meaning, and the barometer by itself cannot indicate with certainty the nature of the coming weather. However, there are some laws which have been found to hold. If the barometer falls rapidly we may expect strong winds; and if it is low, rain or snow is likely to fall. If it is rising, fine weather is probably coming, and if it stays high and steady, fine weather is likely to continue. The barometer is highest in

calm, clear, cold winter weather. Barographs, or self-registering barometers, have been devised on the principle of the aneroid. In these an index carries a pen which makes a continuous record upon a strip of paper on a revolving drum. (Fig. 57).

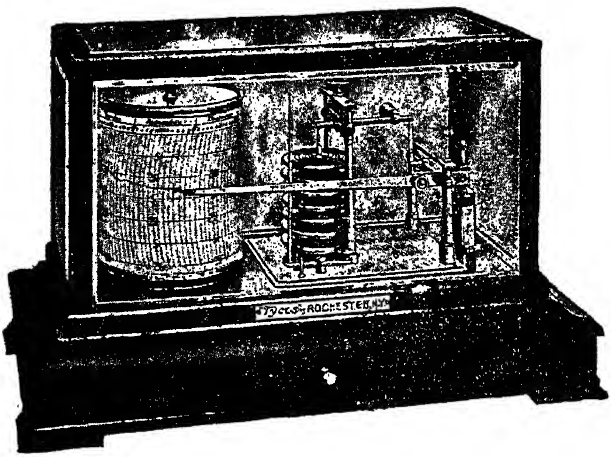


FIG. 57.—Barograph or self-recording barometer.

The normal height of the barometer at sea-level is 76 cm. and when we say that a gas is "at normal pressure" we mean that its pressure is equal to that which would be produced by a column of mercury 76 cm. high.

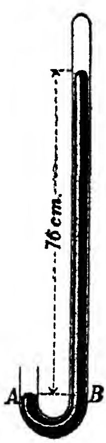


FIG. 58

56. Calculation of Atmospheric Pressure. If we know the barometric height at a given place we can calculate the pressure of the atmosphere there. For example, suppose the barometer stands at 76 cm. (Fig. 58). Then the pressure of the atmosphere at A is equal to the pressure of the mercury at B which is at the same level as A. Consequently to find the atmospheric pressure in grams per sq. cm. we have only to find the weight of a column of mercury 1 sq. cm. in section and 76 cm. in height, that is, the weight of 76 c.c. of mercury.

Taking the density of mercury as 13·6 gm. per c.c., the weight of 76 c.c. will be $76 \times 13{\cdot}6 = 1033{\cdot}6$ gm., and the pressure = 1033·6 gm. per sq. cm.

Now mercury expands as its temperature rises, and consequently the weight of 1 c.c. of mercury depends on the temperature. This must be taken into consideration in making accurate measurements.

By similar reasoning, when the height of the barometer is 30 in., the atmospheric pressure on 1 sq. in. is equal to the weight of 30 cu. in. of mercury. The density of mercury is about 0·49 lb. per cu. in.

Hence, the pressure $= 30 \times 0{\cdot}49 = 14{\cdot}7$ pd. per sq. in.

The records of the Dominion of Canada Meteorological Service show the following maximum and minimum readings of the barometer at Toronto: Jan. 8, 1866, 30·940 in.; Jan. 2, 1870, 28·166 in. By taking 1 in. =2·54 cm. (see Table on the page before page 1) these values are 785·9 and 715·4 mm. respectively.

QUESTIONS AND PROBLEMS

1. If the mercury barometer stands at 76 cm., how high will one filled with alcohol stand? (S. G. of alcohol, 0·8; of mercury, 13·6.)

2. During a storm the mercury in a barometer fell from 30 to 28·5 inches. If the area of the surface of a person is 12 sq. ft., what was the change in the force or thrust of the atmosphere upon him?

3. If the density of the air, like that of water, were uniform throughout its volume, how high would the atmosphere extend, assuming the height of the water barometer to be 34 ft. and the density of air to be 0·081 lb. per cu. ft.?

4. Find the thrust of the atmosphere upon 1 sq. metre when the barometer stands at 75 cm.

5. If a barometer reads 30 in. at sea-level and 20 in. at the summit of a mountain would it read 25 in. half-way up? Explain.

CHAPTER XI

EXPLORING THE ATMOSPHERE AND WEATHER FORECASTING

57. Determination of Elevation. Since the pressure of the air decreases gradually with increase in height above the sea-level, it is evident that the barometer may be utilized to determine changes in elevation. Aneroid barometers are actually used to determine heights in reconnaissance surveying, and the altimeter of an aeroplane consists of an aneroid barometer calibrated in feet of elevation.

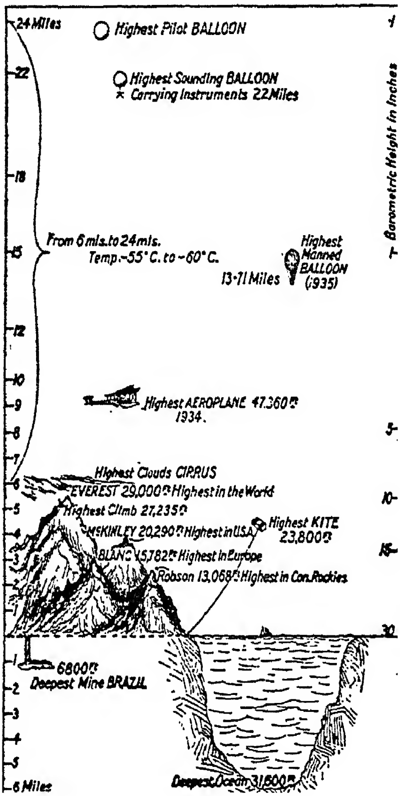


FIG. 59.—Atmospheric conditions at different heights

If the density of the air were uniform, its pressure, like that of liquids, would vary directly as the depth. But on account of the compressibility of air, its density is not uniform; the lower layers, which sustain the greater weight, are denser than those above them. For this reason the law giving the relation between the barometric pressure and the altitude is somewhat complex. For small elevations it falls at an approximately uniform rate of one inch for every 900 feet of elevation.

Fig. 59 shows roughly the conditions of atmospheric pressure at heights up to 24 miles. From the barometric heights at the right side of the figure one learns that half of the total mass of the air is contained within a height of $3\frac{1}{2}$ miles and that only one-thirtieth remains after an altitude of 15 miles is reached.

58. Height of the Atmosphere. There are several ways of obtaining an estimate of the height of the atmosphere, but no means of determining that height accurately. From twilight effects a height of about 40 miles has been calculated. It would seem that above this height the air ceases to reflect light, but other evidence shows that it extends far beyond. Meteors, or shooting stars, which consist of small masses of matter made incandescent by the heat produced as they rush through the atmosphere, have been observed at heights of over 100 miles. The aurora borealis, or northern lights, is probably a phenomenon in our atmosphere, and measurements of brilliant displays seen in the north of Norway show that it usually attains a height of 110 km. (70 mi.) and sometimes even 600 miles.

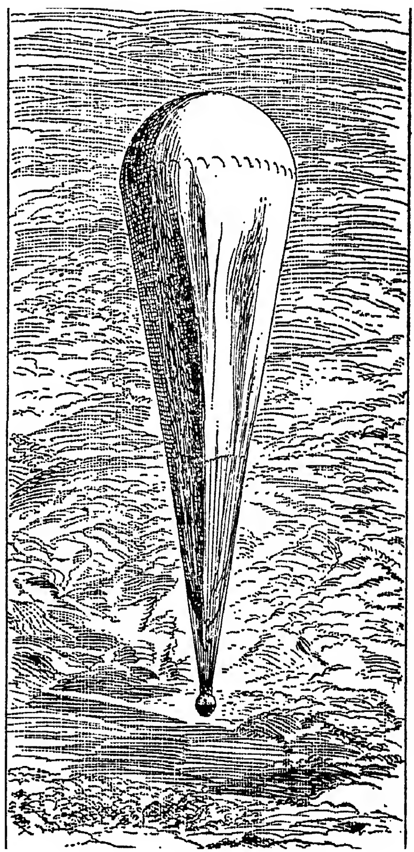


FIG. 60.—Stratosphere balloon "Explorer II".

59. Exploring the Atmosphere. A knowledge of conditions in the atmosphere at considerable distances above the earth is valuable in connection with weather forecasting and aeronautics. Much useful information has been obtained in recent years by means of small rubber balloons carrying light instruments which record the pressure and temperature. The balloon is filled with hydrogen gas, and continually expands as it rises, until it finally bursts. The instruments, attached to a parachute, then fall safely to earth and are returned to the meteorological office by the finder.

By means of these balloons it has been shown that up to a height of six or seven miles the temperature falls steadily, while above this height the temperature is fairly constant (Fig. 59). The lower layer is called the troposphere and the upper the stratosphere.

In 1932 Piccard of Brussels inclosed himself in an air-tight aluminium sphere supplied with oxygen and was carried up by a balloon to a height of 54,450 feet. Since then several similar ascents have been made, the most notable to date being that of Capt. A. W. Stevens and Capt. O. A. Anderson of the United States Army Air Corps, in November, 1935. Their balloon, shown in Fig. 60, had a capacity of 3,700,000 cu. ft. and was filled with helium. At the take-off it towered 316 feet into the air and weighed, with gondola, instruments and crew, 15,000 pounds. The height reached was 72,395 ft. or 13·71 miles.

60. Construction of the Weather Map. The Meteorological Service has stations in all parts of the country at which observers regularly record at stated hours of each day the prevailing meteorological conditions. Twice each day these simultaneous observations are sent by telegraph to the head office at Toronto. These reports include: The barometer reading, the temperature, the direction and velocity of the wind; the rainfall, if any; type and amount of clouds and their direction and speed of motion; barometer tendency; dew-point temperatures and visibility. The information thus received is entered upon a map, a general outline of which is shown in Fig. 61. Places having equal barometric pressures are joined by lines called isobars, the successive lines showing difference in pressure due to $\frac{1}{10}$ inch of mercury. The circles show the state of the weather and the arrows indicate the direction and force of the wind.

Fig. 61 shows the distribution of atmospheric pressure at 8 a.m. on February 4, 1936. The areas of high pressure over the western States and northwestern Canada indicate air masses of Arctic origin. The low area over the Great Lakes entered the continent over the middle Pacific States on February 1, moved eastward to the southwest States and thence in a northeasterly direction owing to a strong current of warm moist air

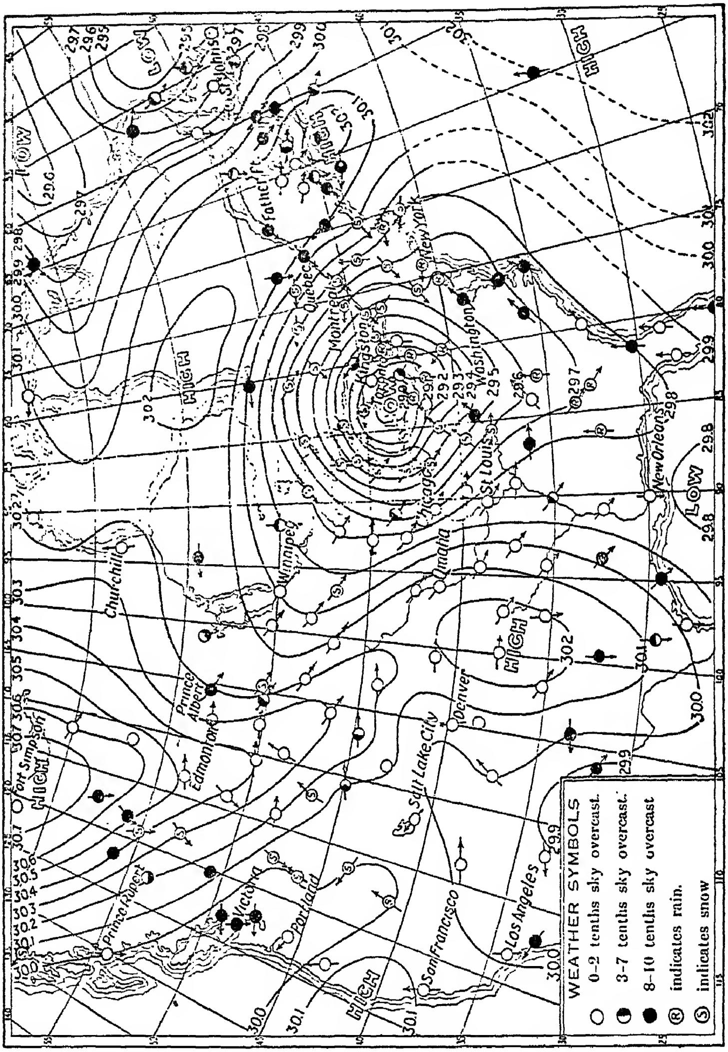


FIG. 61.—Weather Map issued at Toronto for 8 a.m., February 4, 1936. The curved lines, called *isobars*, join places where the height of the barometer is the same. The arrows show the direction of the wind.

FORECASTS. *Lower Lake Region and Georgian Bay:* West to northwest gales; becoming much colder tonight and Wednesday with some snow, chiefly in west portion. *Northern Ontario:* Strong northeast to northwest winds with snow. Wednesday, northwest winds; partly cloudy and decidedly cold; snowflurries. *Ottawa and Upper St. Lawrence Valleys:* Strong east to southeast winds with snow or sleet, followed by strong northwest winds and

much colder again late tonight and Wednesday. *Lower St. Lawrence Valley:* Strong northeast winds with snow, probably part sleet. Wednesday, strong westerly winds; partly cloudy and cold with snowflurries. *Maritime Provinces.* Easterly gales with snow and sleet tonight and part of Wednesday. *Lake Superior.* Strong northeast to northwest winds; cloudy and cold with some snow, chiefly in east portion. Wednesday, northwest winds; partly cloudy and decidedly cold with snowflurries near the Soo. *Western Provinces:* Mostly fair and decidedly cold today and Wednesday.

from the Gulf of Mexico entering the continent over the eastern States. This current is known as "Gulf air". The spiral in-blowing of winds from the high-pressure to the low-pressure is well shown on the map. As the low area continued to move in a northeasterly direction towards Ungava, the cold Arctic air spread into Ontario on the 5th and 6th, with temperatures generally below zero.

On account of the difference in pressure in the area there is a motion of the air inwards towards the centre of the "low," and outwards from the centre of the "high." But these motions are not directly towards or away from the centre. An examination of the arrows on the map will show that there is a motion about the centre. In the case of the "low" this motion is contrary to the direction of motion of the hands of a clock, while in the case of the "high" the motion is with the hands of the clock. Through a combination of the motions the air moves spirally inwards to the centre of low pressure and spirally outwards from the centre of high pressure. The system of winds about a centre of low pressure is called a cyclone, that about a centre of high pressure, an anti-cyclone. The disturbance in the cyclone is usually much greater than in the anti-cyclone.

At the centre of low pressure there is an ascending current of air, which rises until it reaches a great height, when it flows over into the surrounding regions. In the case of the area of high pressure there is a flow of air from the upper levels of the surrounding atmosphere into the centre of high pressure, thus raising the barometer.

It will be observed, also, that while the air in an area of low or high pressure may be only three or four miles high, these areas are hundreds of miles across.

Now it has been found that within the tropics, in the trade-wind zones, the drift of the atmosphere is towards the west and south, and disturbances are infrequent; but in higher latitudes the general drift is eastward, and disturbances are of frequent occurrence, especially during the colder months. Thus in Canada and the United States the areas of high and low pressure move in an easterly direction.

61. Elementary Principles of Forecasting. In using the weather map the chief aim is to foresee the movement of the areas of high and low pressure and the attending air masses, and to predict their positions at

some future time, say 36 hours hence. It is also essential to judge rightly what changes will occur in the energy of the areas shown on the map, as these changes will intensify or otherwise modify the atmospheric conditions.

The formation and development of cyclonic areas can usually be foreseen by pressure tendencies, wind circulations and sharp temperature gradients.

As the cyclone moves eastward, the first indication of its approach will be the shifting of the wind to the eastward. The direction in which the wind will veer depends on whether the storm centre passes to the northward or the southward; and the strength of the wind will depend on the closeness of the isobars. If they are close together, the wind will be strong. If the centre passes nearly over a place, the wind will chop round to the westward very suddenly; while if the centre is at a considerable distance, the change will be more gradual.

The precipitation (rain or snow) in connection with a cyclonic area is largely dependent on the energy of the disturbance and the sources of the air masses attending it. It must, of course, be remembered that rain cannot fall unless there is moisture, and moisture will not be precipitated unless the volume of the air containing it is cooled below the dew-point.

The region where one air mass displaces another is frequently referred to as a "front" and it is usually in these regions that unsettled weather occurs. Precipitation occurs under one of three main processes: Where warm moist air over-runs colder air; where incoming cold air under-runs relatively warm moist air, or in thunder-storm formations.

The duration of precipitation or winds of any particular direction depends upon the rate of movement of the air masses. Temperature changes in any given region can also be arrived at only by accurate estimation or computation of the movement of these masses and the amount of heat, lost or gained by radiation or insolation (exposure to the sun).

Abnormally warm weather in Ontario results from the slow movement of warm air from the southern and southwestern States, slowly increasing in intensity owing to insolation. Cold waves are the result of rapidly moving air masses of Polar origin towards the central and eastern portions of the continent.

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CHAPTER XII

BUOYANCY OF GASES; BOYLE'S LAW

62. Buoyancy of Gases. If we consider the cause of buoyancy, as explained in § 41, we must recognize that Archimedes' Principle applies to gases as well as to liquids. A simple experiment to demonstrate the buoyant force of air is illustrated in Fig. 62. A hollow metal or glass globe *A* is suspended from one end of a short balance beam and is counterpoised by a small weight *B*. If the air exerts a buoyant force, as in a liquid, the force upward on *A* must be greater than that on *B*, and if the air be removed from about the balance the globe *A* should sink. On putting the apparatus under the receiver of an air-pump and exhausting the air, the globe slowly sinks.

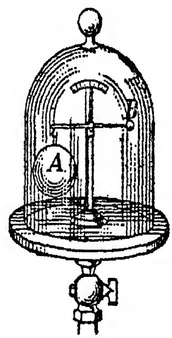


Fig. 62.—Demonstrating buoyancy of the air.

A gas exerts upon a body immersed in it a buoyant force which is equal to the weight of the gas displaced by the body. Consequently, if a body is lighter than the weight of the air which it displaces, it will rise in the air, just as a cork, let free at the bottom of a pail of water, rises to the surface.

63. Balloons and Air-Ships. The use of air-ships or balloons is made possible by the buoyancy of the air. A balloon is a large, light, gas-tight bag filled with some gas lighter than air, usually hydrogen or illuminating gas. Helium is the ideal gas for the purpose as it will not take fire, but at the present time there is not enough of it available for general use. In Fig. 63 is illustrated the great British air-ship R-34, which, during the summer of 1919, made the journey from Great Britain to the United States and back. By means

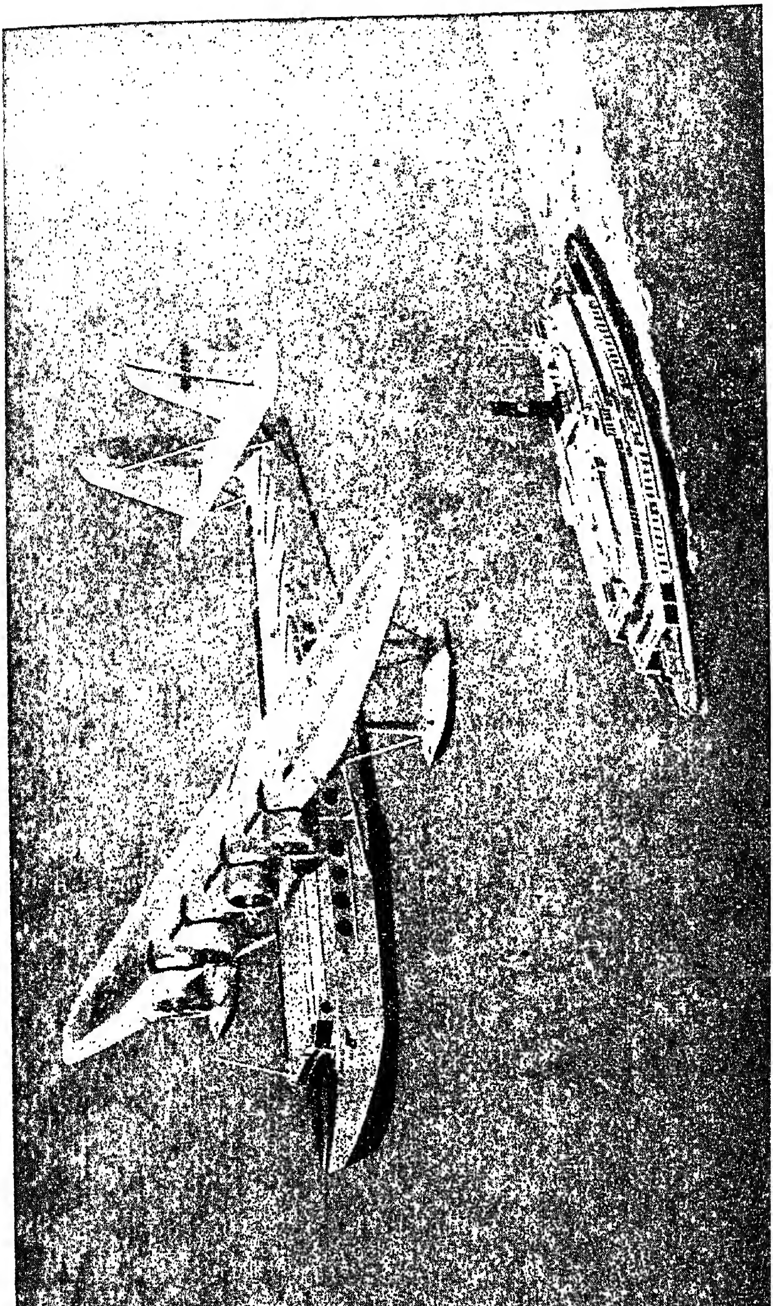
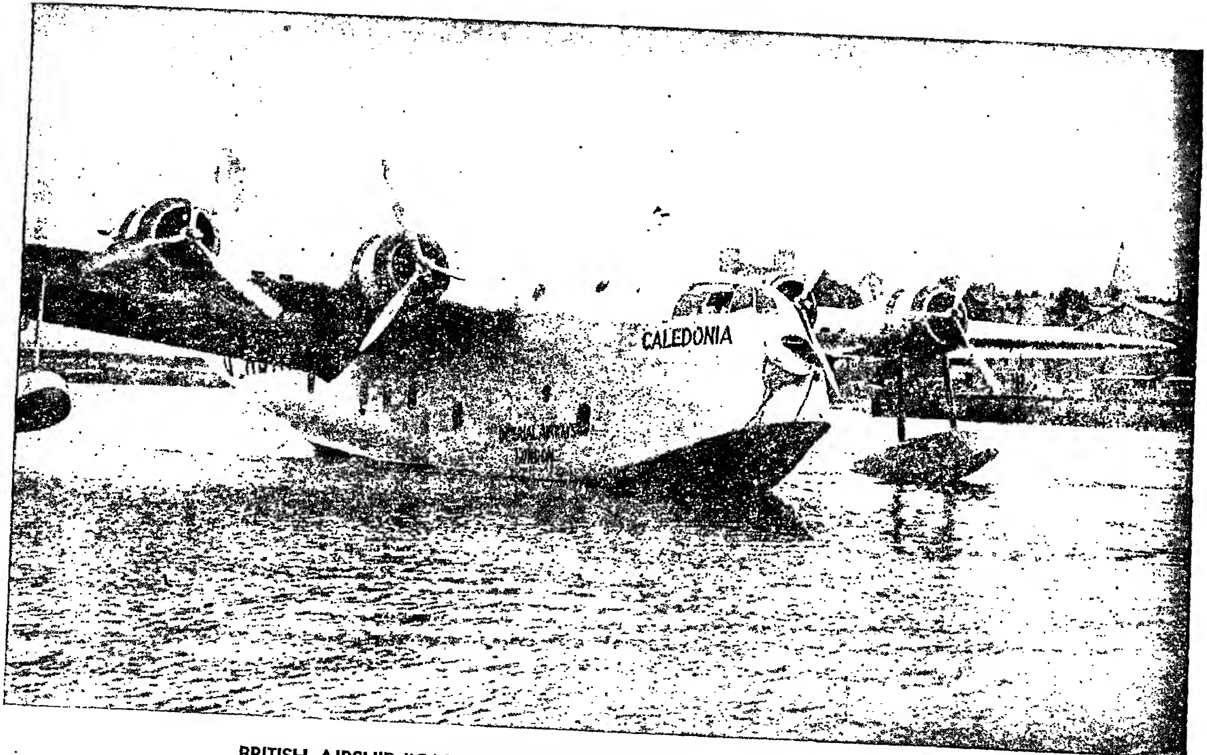


Plate 4

The aeroplane is leaving California June 12, 1935, for its first regular trip to the Philippine Islands. It reached Honolulu, 2,400 miles in 17 h. 57 m. Its length is 89 ft. 6 in.; weight, 51,000 lb.; and it can carry 46 passengers.

The steamer below is a San Francisco-Oakland Ferry-boat.



BRITISH AIRSHIP "CALEDONIA" OF IMPERIAL AIRWAYS. LONDON

Plate 5

• **Plate 5**

This ship left Foynes, Ireland, for Botwood, Nfld., on its way to New York, on July 5, 1937. It reached Botwood, 2000 miles, in 15 h. 28 m. An American ship, "Clipper III," at the same time made the easterly trip from Botwood to Foynes in 12 h. 29 m.

of propellers these air-ships can be driven in any desired direction.

In May, 1936, the German air-ship Hindenburg began regular trips to the United States. It is 803 ft. long and 135 ft. in diameter, with a volume of 7,063,000 cu. ft. and gross weight 431,000 pounds. It was lost May 6th, 1937.

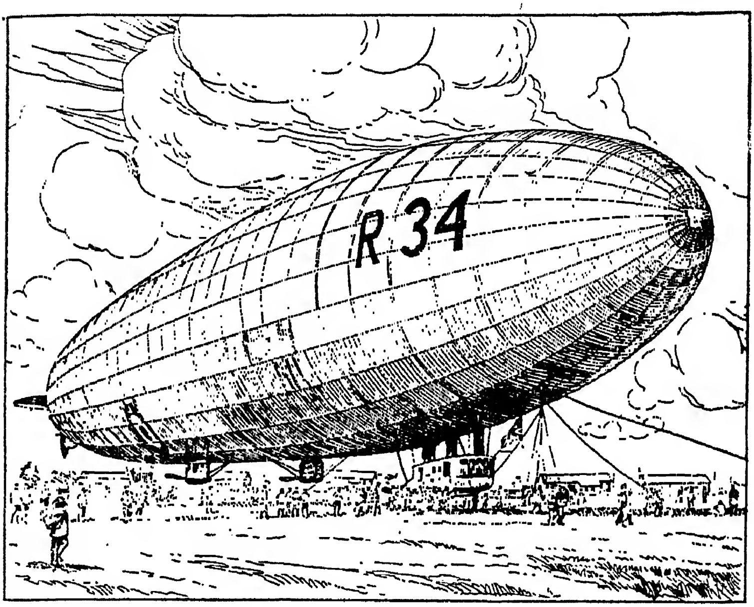


Fig. 63.—The British air-ship R-34, the first to cross the ocean. It left East Fortune, Scotland, July 2, and reached Long Island, N.Y., July 6, 1919. Time of fight, 108 hours. The return was made in 75 hours. Length, 672 ft.; diameter, 79 ft.; volume 2,000,000 cu. ft.; crew and passengers, 30.

A balloon will continue to rise so long as its weight is less than the weight of the air which it displaces, and when there is a balance between the two forces it simply floats at a constant height. In the case of an ordinary balloon the aeronaut maintains his position by adjusting the weight of the balloon to the buoyancy of the air. When he desires to ascend, he throws out ballast. To descend he allows gas to escape and thus decreases the buoyancy. The air-ships

described are made to rise or sink, or turn to the right or left by means of suitable elevators and rudders.

64. Lifting Power of a Balloon. It will be interesting to compare the lifting powers of a balloon filled with different gases. Let its capacity be 2,000 cu. metres (about 70,600 cu. ft.). If it were spherical the diameter would be 51·3 ft.

The weight of 1 cu. m. of hydrogen = 0·09 kg.; of helium, 0·18 kg.; of illuminating gas, 0·75 kg.; of air, 1·29 kg. (at standard pressure and temperature).

Hence the weight of 2000 cu. m. of hydrogen = 180 kg.; of helium, 360 kg.; of illuminating gas, 1500 kg.; and the same volume of air weighs 2580 kg., which is the buoyant force of the air (neglecting the volume of the material of the balloon and its basket).

The lifting force, therefore, if the balloon is filled with

Hydrogen	= 2580 − 180 = 2400 kg.
Helium	= 2580 − 360 = 2220 "
Illuminating gas	= 2580 − 1500 = 1080 "

Thus the lifting power of helium is about $\frac{11}{12}$, while that of illuminating gas is $\frac{9}{20}$ that of hydrogen.

QUESTIONS AND PROBLEMS

1. Why should the gas-bag be subject to an increased strain from the pressure of the gas within as the balloon ascends?

2. Aeronauts report that balloons have greater buoyancy during the day when the sun is shining upon them than at night when it is cold. Account for this fact.

3. If the volume of a balloon remains constant, where should its buoyancy be the greater, near the earth's surface or in the upper strata of the air? Give reasons for your answer.

4. An aluminium block is placed on one pan of a balance and a lead weight on the other and they are in equilibrium? The whole is put in a vessel and the air removed from it. Describe what happens and explain why.

5. The volume of a balloon is 2,500 cu. m. and the weight of the gas-bag and car is 100 kg.; find its lifting power when filled with hydrogen gas, the density of which is 0·0000899 gm. per c.c. while that of air is 0·001293 gm. per c.c. (at standard pressure and temperature.)

6. Find the lifting power of the same balloon when filled with helium, which is twice as dense as hydrogen.

7. If the balloon were filled with illuminating gas, which is 8 times as dense as hydrogen, would it rise? If so, find the lifting power.

8. A balloon had a capacity of 80,000 cu. ft. The gas-bag, net about it, and the basket together weighed 985 pounds. How great a load could it carry when filled with hydrogen? (1 cu. ft. air = 0·08 lb.; of hydrogen = 0·0056 lb.)

9. The ordinary balloons used during the Siege of Paris in 1870 had a capacity of about 70,000 cu. ft. and the weight of the balloon and car was about 1000 pounds. Find the lifting power when filled with coal gas whose density is 0·4 that of air.

65. Compressibility and Expansibility of Gases. We have already referred to the fact that gases can be compressed and that they will expand if allowed to do so. If a quantity of gas is introduced into a closed vessel it will spread out and go into every corner of it, no matter what the shape may be.

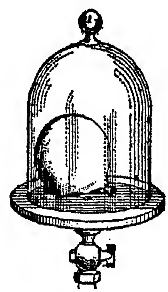


FIG. 64.—When the air is removed from the receiver the toy balloon expands.

In its efforts to escape, the gas exerts a pressure against the walls of the vessel inclosing it. This can be illustrated in the following way. Place a toy balloon or a half-inflated rubber from a football under the receiver of an air-pump and operate the pump. (Fig. 64.) As the air about the bag is continually removed, the bag expands; and when the air is admitted again the bag resumes its former volume.

66. Relation between the Volume and the Pressure of Air—Boyle's Law. The exact relation between the volume of a given mass of gas and the pressure upon it was first determined by Robert Boyle in 1662. While trying to show that the Torricellian phenomenon (§ 49) was due to "the spring of the air" he devised an experiment which showed that the volume of a given quantity of air varies inversely

as the pressure to which it is subjected. He took a U-tube of the form shown in Fig. 65, and, by pouring in enough mercury to fill the bent portion, inclosed a definite portion of air in the closed shorter arm. By manipulating the tube he adjusted the mercury so as to stand at the same height in each arm. Under these conditions the imprisoned air was at the pressure of the outside atmosphere, which at the time of the experiment would support a column of mercury about 29 inches high. He then poured mercury into the open arm until the air in the closed arm was compressed into one-half its volume. "We observed," he says, "not without delight and satisfaction, that the quicksilver in that longer part of the tube was 29 inches higher than the other." Clearly the pressure upon the inclosed air was that produced by 29 inches of mercury and the atmosphere on its free surface. Consequently, the pressure sustained by the inclosed air was doubled when the volume was reduced to one-half. Continuing his experiment, he showed, on using a great variety of volumes and their corresponding pressures, that if the volume is reduced to $\frac{1}{3}$, the pressure is 3 times as great, if the volume is $\frac{1}{4}$, the pressure is 4 times as great, and so on.

FIG. 65.—Boyle's apparatus

From this experiment we learn that

The pressure and volume of a gas vary in such a way that the product $P \times V$ is constant. (Temperature assumed constant).

Or in other words—

If the temperature is kept constant, the volume of a given mass of gas varies inversely as the pressure to which it is subjected.

This relation is generally known as BOYLE'S LAW.*

*In France it is called Mariotte's Law, having been independently discovered by Mariotte in 1676.

67. Alternative Boyle's Law Experiment. Fig. 66 illustrates another form of apparatus suitable for demonstrating Boyle's Law.

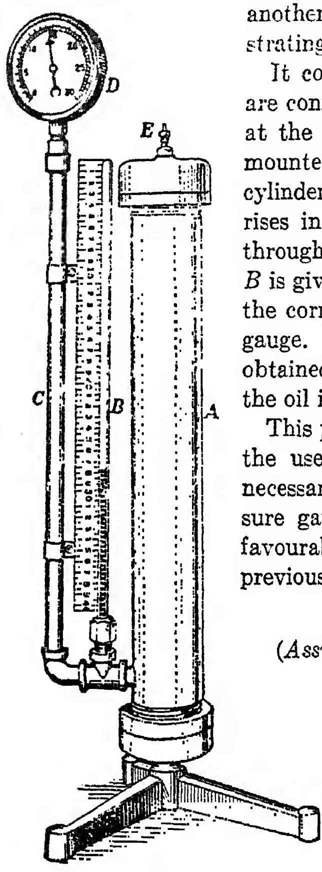


FIG. 66.—Ahrens' apparatus for Boyle's Law.

It consists of the large reservoir A to which are connected the glass tube B, which is closed at the top and the metal tube C on which is mounted the pressure gauge D. The large cylinder is partly filled with a light oil which rises in B and C when air is pumped into A through the valve E. The volume of the air in B is given by the scale mounted alongside B and the corresponding pressure is read on the pressure gauge. Pressures less than atmospheric may be obtained by exhausting air from the space above the oil in A.

This piece of apparatus is easily manipulated, the use of mercury is avoided and it is not necessary to read the barometer. If a good pressure gauge is used the results compare very favourably with those obtained by the method previously described.

QUESTIONS AND PROBLEMS

(*Assume the temperature remains constant.*)

1. A partially inflated balloon swells out more and more as it rises. Explain.

2. A bottle partly filled with water is closed with a perforated cork and connected by a bent tube with an uncorked bottle as shown in Fig. 67. Explain what happens when this arrangement is placed under the receiver of an air-pump and the air is exhausted.

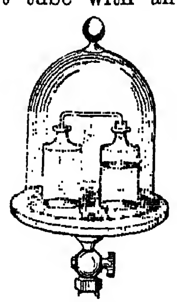


FIG. 67.

3. A tank whose capacity is 2 cu. ft. has gas forced into it until the pressure is 250 pd. per sq. inch. What must be the capacity of a tank to hold the same mass of gas when the pressure is 75 pounds per sq. inch?

4. A gas-holder contains 22·4 litres of gas when the barometer stands at 760 mm. What will be the volume of the gas when the barometer stands at 745 mm.?

5. A cylinder whose internal dimensions are: length 36 in., diameter 14 in., is filled with gas at a pressure of 200 pd. per sq. inch. What volume would the gas occupy if allowed to escape into the air when the barometer stands at 30 in. (Take density of mercury as 848 lb. per cu. ft.).

6. Twenty-five cu. ft. of gas, measured at a pressure of 29 in. of mercury, is compressed into a vessel whose capacity is $1\frac{1}{2}$ cu. ft. What is the pressure of the gas?

7. A mass of air whose volume is 150 c.c. when the barometer stands at 750 mm. has a volume of 200 c.c. when carried up to a certain height in a balloon. What is the reading of the barometer at that height?

8. A piston is inserted into a cylindrical vessel 12 in. long, and forced down within 2 in. of the bottom. What is the pressure of the inclosed air if the barometer stands at 29 in.?

9. The density of the air in a gas-bag is 0·001293 gm. per c.c. when the barometer stands at 760 mm.; find its density when the barometric height is 740 mm.

10. An open vessel contains 100 gm. of air when the barometer stands at 745 mm. What mass of air does it contain when the barometer stands at 755 mm.?

11. Oxygen and other gases, used for welding and other purposes, are stored in steel tanks. The volume of a tank is 6 cu. ft., and the pressure of the gas at first was 15 atmospheres. After some had been used the pressure was 5 atmospheres. If the gas is sold at 6 cents a cu. ft., measured at atmospheric pressure, what should be charged for the amount consumed?

12. In one form of sounding apparatus a slender glass tube closed at one end is lowered, open end down, to the bottom of the ocean, and an ingenious arrangement allows one to see, when the apparatus has been brought up to the surface, to what height the water had risen in the tube. Suppose that the tube is 45 cm. long and the water rises to within 1·5 cm. of the closed end.

(*a*) What pressure (in atmospheres) has the inclosed air been subjected to?

(*b*) Taking the barometric height to be 76 cm.; the sp. gr. of mercury to be 13·6 and that of sea-water to be 1·026, find the depth of the water.

CHAPTER XIII

AIR-PUMPS AND AIR APPLIANCES

68. Air-pump. Fig. 68 shows the construction of a simple pump used for exhausting air from a vessel. When the piston P is raised, the valve V_1 is closed by its own weight and the pressure of the air above it. The expansive force

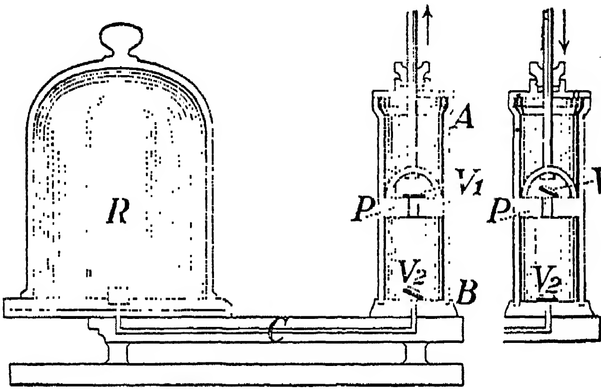
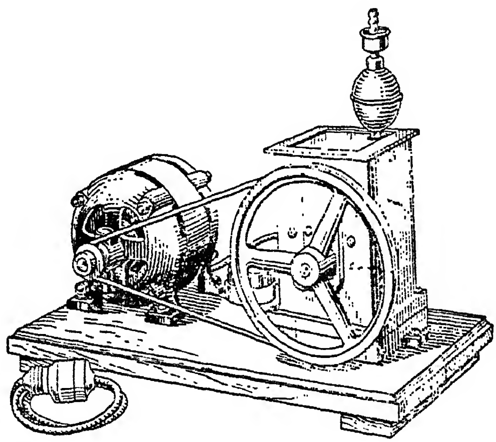


FIG. 68.—Simple form of air-pump. AB, cylinder of pump; R, receiver from which air is to be exhausted; C, pipe connecting cylinder with receiver; P, piston of pump; V_1 and V_2, valves opening upwards.

of the air in the receiver lifts the valve V_2, and a portion of the air flows into the lower part of the cylinder. When the piston descends, (see figure at right) the valve V_2 is closed, and the air in the cylinder passes up through the valve V_1. Thus at each double stroke, a fraction of the air is removed from the receiver. The process of exhaustion will cease when the expansive force of the air in the receiver is no longer sufficient to lift the valve V_2, or when the pressure of the air below the piston fails to lift the valve V_1. It is evident, therefore, that a partial vacuum only can be obtained with a pump of this kind. To secure more complete exhaustion, pumps in which the valves are opened and closed automatically by the motion of the piston are frequently used, but even with these all the air cannot be removed from the receiver, because

at each stroke the air in the receiver is reduced only by a *fraction of itself.*

69. Rotary Air-pump. This modern type of pump (Fig. 69) will exhaust air to a pressure of ·001 mm. It is of light weight, and is reliable and quiet in operation. It is also much more rapid in its action than the ordinary air-pumps.



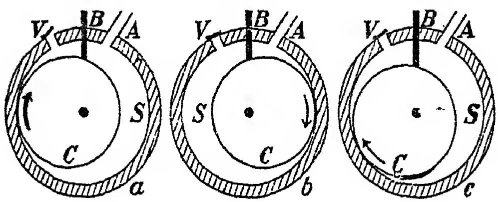


FIG. 69.—A rotary air-pump. In *a, b, c* is shown a vertical section of the cylinder at different stages of a rotation.

Within the outer case of the pump is a fixed hollow cylinder provided with an inlet tube *A* and an outlet which is fitted with a valve *V*. Inside this cylinder is a second cylinder *C* mounted eccentrically on an axle which is driven by a large pulley. As the inner cylinder rotates, it is always in contact with a portion of the outer cylinder. A metal plate *B* works up and down through a slot cut in the outer cylinder, always resting on the rotating cylinder. The pump case is filled with oil so that only the inlet tube *A* projects.

In position *a* the space *S* is in communication with the inlet tube *A*, which is connected to the vessel from which the air is being removed. As the cylinder rotates in the direction of the arrow to position *b*, the air

in S is cut off from that in the vessel and is compressed, while new air from the vessel is entering through A. In position c most of the air which was in S in position b has been driven out through the valve V while the new space S is nearing its maximum size. As the rotation continues, position a is reached again and the cycle repeats.

70. Bunsen Jet Pump. Bunsen devised a simple and convenient form of pump, which is much used in laboratories where a moderate exhaustion is required, as for hastening the process of filtration. In this pump (Fig. 70) water under a pressure of more than one atmosphere is forced into a jet through a tube nozzle N. The air is carried along by the water and is thus withdrawn from any vessel connected with the offset tube A.

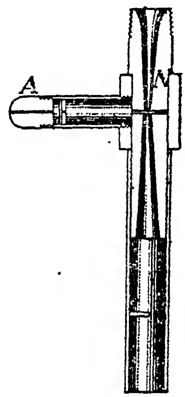


FIG. 70.—Bunsen jet pump.

71. Air Compressors. A simple air compressor is shown in Fig. 71. When the piston A is at rest both valves are closed. As the piston moves upward, a partial vacuum is formed below it and the air outside pushes valve B open and enters the cylinder. At the top of the stroke B closes. On the downstroke of the piston, C opens as soon as the pressure inside the cylinder becomes great enough to overcome the weight of the valve and the opposing pressure exerted by the air on the other side of it. The outlet may be attached directly to a tire or to a tank in which air is to be stored. This pump may also be used to exhaust air from a vessel attached to the inlet.

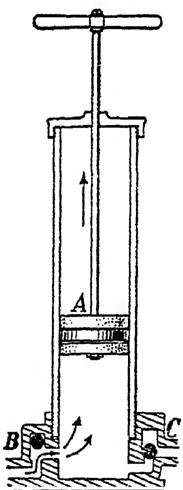


FIG. 71.—A simple air compressor.

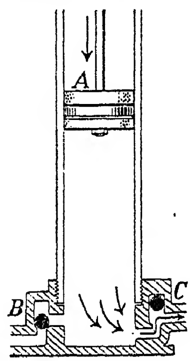


FIG.—71a

The ordinary automobile pump (Fig. 72) has no valves. On the up-stroke of the piston P, air flows into the cylinder past the soft cup-shaped leather which forms part of the piston. When the piston is moving downward, this leather is pressed tightly against the inside of the cylinder and the compressed air is forced out of the tube at the bottom and through a valve attached to the inner tube of the tire.

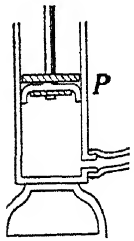


FIG. 72. — Ordinary automobile pump.

A motor-driven compressor is illustrated in Fig. 73. The motor A drives a wheel B on the opposite end of whose shaft is the crank disc C to which the piston rod D is attached. This causes the piston E to move up and down in the cylinder F. As the piston rises, air is drawn in through the intake I and goes past the valve G into the cylinder. As it descends, this air is forced through the valve H into the tank K. The air is rapidly driven into the tank and the pressure, which is measured by the gauge L, quickly rises.

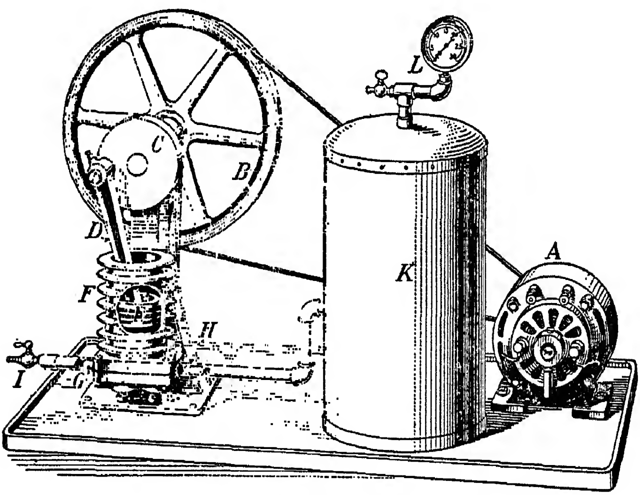
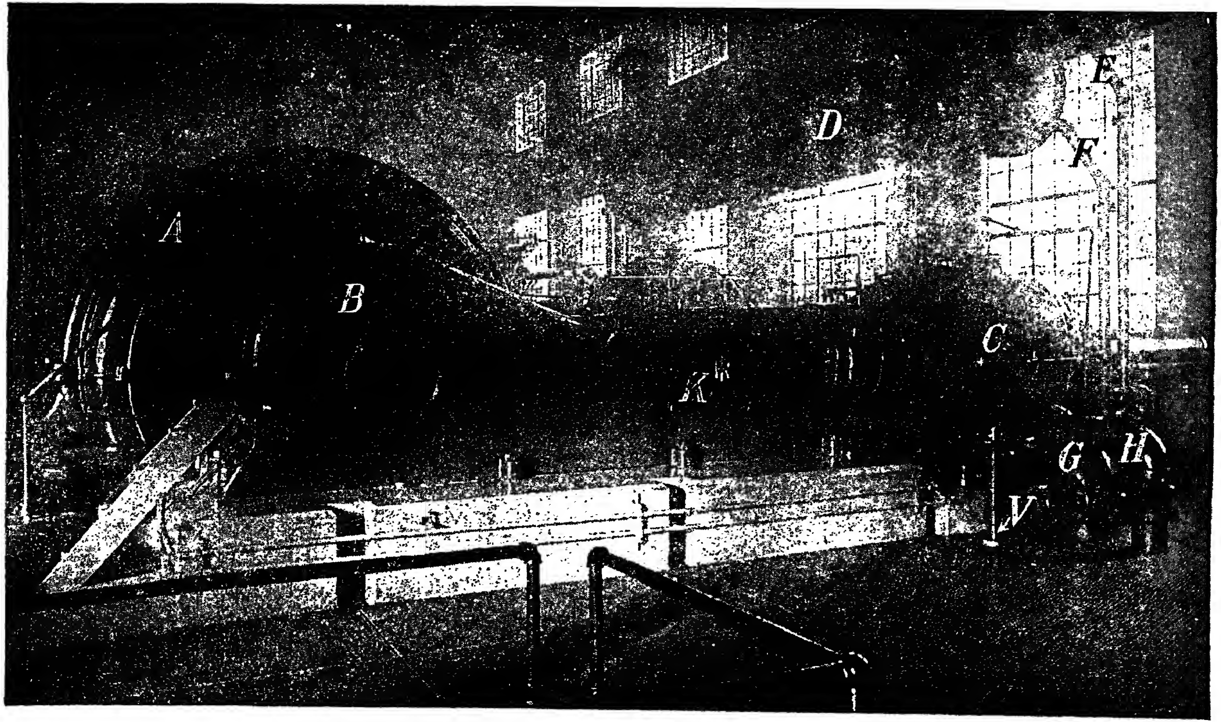


FIG. 73.—A motor-driven compressor.

72. Hydraulic Air Compressor. The energy of falling water may be used to compress air without any mechanical moving parts being employed. An application of this principle is to be seen in the great air compressor at Ragged Chutes, on the Montreal River, eight miles south-west from Cobalt, the centre of a mining region in northern Ontario.

A cement dam 660 feet long across the river raises the level of the water. By a large tube A (Fig. 74) the water is led into two vertical pipes P



AIR COMPRESSOR AT THE HOLLINGER MINES, TIMMINS, ONT.

Plate 6

• Plate 6

This big machine compresses 9,500 cu. ft. of free air per minute to a gauge pressure of 100 pd. per sq. in. It has a low and a high compression cylinder, the former being on the far side of the 1,500 h.p. motor *A* which drives both. On each end of the shaft of the motor is a crank. That within the case *B* supplies through the crosshead inside the case *K* the energy to operate the piston in the high-pressure cylinder *C*. On the other side of the motor is a similar crank and crosshead operating the piston in the low-pressure cylinder.

Air is drawn into the low-pressure cylinder, compressed to 31 pd. and discharged through the inter-cooler *D* to the high-pressure cylinder *C*, where it is further compressed to 100 pd. Pipe *H* assists in starting, *G* is opened by valve *V* to the main supply lines. Pipes *E* and *F* provide water to circulate in the inter-cooler. There are four other compressors, and the air is used chiefly for operating pneumatic rock drills.

(Photograph supplied for this book by the Hollinger Mines)

(only one shown in the figure), 16 feet in diameter into each of which is fitted a framework holding 66 intake pipes *a*, *a*, 14 inches in diameter. The water-line is about 10 or 12 inches above the top of the nest of intake pipes. In descending the water forms a vortex in the mouth of each pipe through which air is drawn down into the shaft below. Thus air and water are mixed together. At *b* the pipe is reduced to 9 feet and near the bottom, at *c*, is enlarged to $11\frac{1}{2}$ feet in diameter.

The water drops 350 feet, falling on a steel-covered cone *B*, from which it rushes into a horizontal tunnel over 1000 feet long, the farther end *d* of which is 42 feet high. In this large channel the water loses much of its speed and the air is rapidly set free, collecting in the upper part of the tunnel. At *e* the tunnel narrows and the water races past and enters the tail-shaft *T*, 300 feet high, from which it flows into the river again.

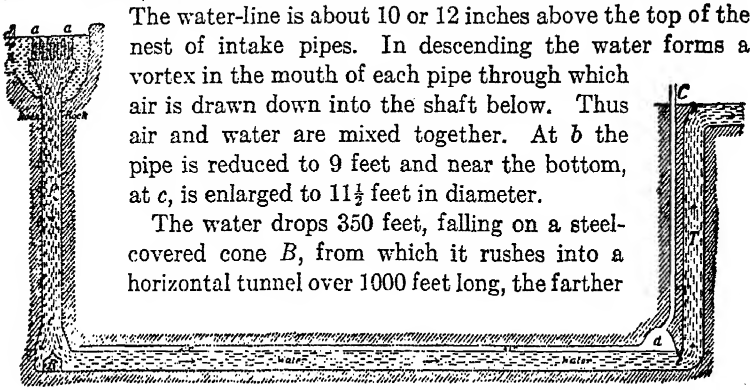


FIG. 74.—Taylor air compressor at Ragged Chutes on Montreal River (section).

The air entrapped in the tunnel is under a pressure due to about 300 feet of water, or about 125 pounds per square inch. From *d* a 24-inch steel pipe leads to the surface of the earth, and from here the compressed air is piped off to the mines.

73. Bourdon Pressure Gauge. The construction of this useful appliance is shown in Fig. 75. The gauge is attached to a tank or a pipe by the nipple *G*. Within the case is a bent metal tube *A* which is closed at the upper end. When air or water is forced into it under pressure, the tube, which is of elliptical cross-section, tries to straighten out. Now the lower end is rigidly fixed, but the upper end is free to move, and the higher the pressure in the tube the greater is its motion. By means of a metal strip *B* this end is joined to the short arm of the lever *C* which turns about the pin *D*. On the other end of *C* are teeth which mesh with the small pinion *E*, and the hand *F* is on the end of the axis of the pinion.

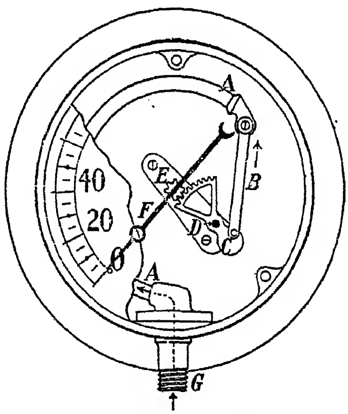


FIG. 75.—Bourdon pressure gauge.

Hence the motion of the free end of the tube A is multiplied and transmitted to the hand, which moves around the dial.

74. Air-Brakes. One of the many uses of compressed air is to set the brakes on railway trains. Fig. 76. illustrates the principal working parts of the Westinghouse air-brakes in common use in this country. A steam-driven air-compressor pump A and a tank B for compressed air are attached to the locomotive. The equipment on each car consists of (i) a cylinder C in which works a piston, directly connected, by a piston-rod D and a system of levers, with the brake-shoe G, (ii) a secondary tank E,

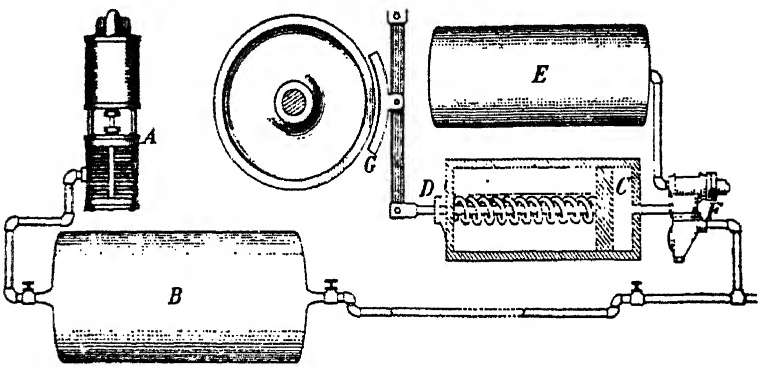


Fig. 76.—Air-brakes in use on railway trains.

and (iii) a system of connecting pipes and a special "triple-valve" F which automatically connects B with E when the air from B is admitted to the pipes, but which connects E with the cylinder C when the pressure of the air is removed.

When the train is running, pressure is maintained in the pipes and in the tank E, and the brakes are free; but when the pressure is decreased, either by the engineer or by the accidental breaking of a connection, the inrush of air from E to C forces the piston forward and sets the brakes against the wheels. To take off the brakes, the air is again turned into the pipes, the valve F then connects B with E and the air in C is allowed to escape, while the piston is forced into its original position by a spring.

Compressed air brakes are also used on street cars and heavy motor vehicles.

75. Pneumatic Caisson. Pneumatic caissons are used in laying the foundations of bridges, piers, and in other submarine work. A section of a typical caisson is shown in Fig. 77. The sides of the caisson are

extended upward and are strongly braced to keep back the water. Masonry, or concrete, C, D, placed on top of the caisson, presses it down upon the bottom, while compressed air, forced through a pipe P drives the water from the working chamber and also sustains the men. To leave the caisson the workman climbs up and passes through the open door B into the air-lock L. The door B is then closed and the air is allowed to escape from L until it is at atmospheric pressure. Then door A is opened and the workman climbs out. In order to enter, this procedure is reversed. Material is hoisted out in the same way or is sucked out by a mud-pump. As the earth is removed, the caisson sinks, until at last the solid rock is reached. The entire caisson is then filled with solid concrete, which forms a permanent foundation for a dock or bridge.

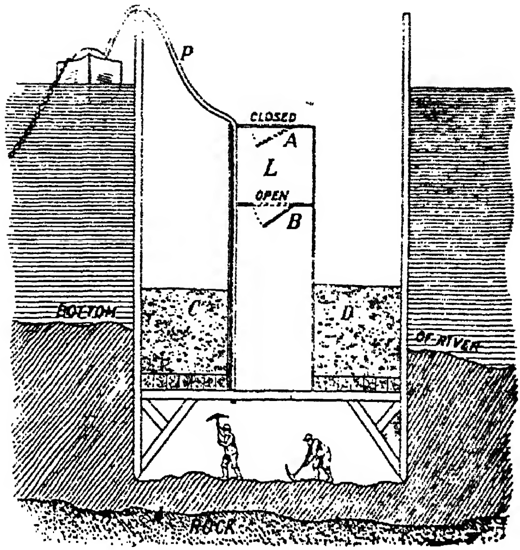


FIG. 77.—Section of a pneumatic caisson.

G. 78.—Diver's suit.

76. Diving Apparatus. The modern diver is incased in an air-tight weighted suit. (Fig. 78). He is supplied with air from above, through pipes or from a compressed-air reservoir attached to his suit. The air escapes through a valve into the water.

Manifestly the pressure of the air used by a diver or a workman in a caisson must balance the pressure of the outside air, and the pressure of the water at his depth. The deeper he descends, therefore, the greater the pressure to which he is subjected. The ordinary limit of safety is about 80 feet but divers have gone much deeper than this. In March, 1915, a United States submarine sank in the harbour of

Honolulu. A diver went 288 feet under water and walked along the top of the ship, and in the course of salvaging it he made five descents to a depth of 306 feet.

More recently still greater depths have been attained by the use of armoured suits which carry their own air supply and enable the divers to breathe air at atmospheric pressure. In 1922 the ship *Egypt,* carrying gold and silver valued at about $5,000,000, was sunk by collision in the Bay of Biscay. The work of salvaging the gold was directed by divers in armoured observation shells and ultimately most of the immense fortune was recovered although the depth was over 400 feet.

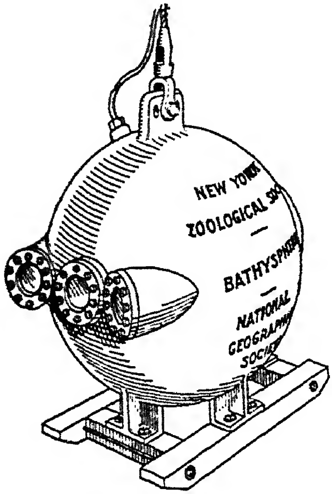


FIG. 79.—Dr. Beebe's bathysphere. Besides the two observers this 4½-ft. sphere contained the following equipment: oxygen tanks, chemicals to absorb carbon dioxide and moisture, camera, telephone, photometer, barometer, spectroscope, stereoglasses, flashlight, searchlight, fan, temperature-humidity recorder, first aid kit, colour chart and books.

Fig. 79 shows the "bathysphere"* in which Dr. William Beebe and Mr. Otis Barton have made several descents into the ocean near Bermuda. The sphere is of steel 4½ feet in diameter and has thick quartz windows for the observation of deep sea fish and other phenomena. The greatest depth reached was 3028 ft. in August, 1934. At this depth the pressure was 1360 pd. per sq. in. and each window had to sustain a thrust of more than 19 tons.

77. Submarines. A submarine (Fig. 80) carries powerful air compressors and tanks for the storage of compressed air. These tanks are filled while the boat is on the surface.

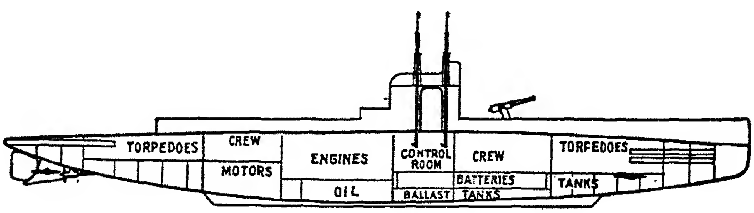


FIG. 80.—Section of a submarine.

*The Greek word *bathys* means deep.

In order to submerge, water is admitted to the water-ballast tanks until the submarine is just on the point of sinking. The depth below the surface is then controlled by operating the horizontal diving rudders shown near the bow and stern in the diagram.

When it is desired to have the boat float on the surface the water is forced from the ballast tanks by connecting them to the compressed-air tanks. Powerful pumps are provided for use if the compressed air fails. The stored air is also used for discharging torpedoes and for renewing the air which has been vitiated by breathing.

78. Compressed Air Tools. Another device making use of compressed air is the pneumatic drill used chiefly for boring holes in rock for blasting. In it the steel drill is held in the end of a cylinder within which a piston is made to move back and forth by allowing compressed air to act alternately on its two end faces. Each time the piston moves forward it delivers a vigorous blow upon the end of the drill, and as it does this several times per second the drill enters the rock quite rapidly. The pneumatic hammer, which is similar in principle, is used for riveting and in general foundry work.

The details of a paving breaker are shown in Fig. 81. When the trigger A is pressed, air enters by the inlet C and flows past the valve B into the top of the cylinder. The air then passes through the opening opposite D and enters the lower part of the cylinder by the port E. The pressure of this air starts the piston F on its up stroke and also raises the valve G, allowing a greater flow of air into the bottom of the cylinder.

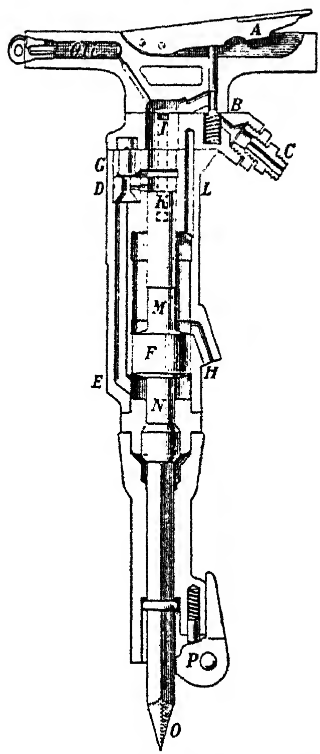


Fig. 81.—A paving breaker. The letters G, D, E and L are placed opposite the parts to which they refer.

As the piston rises, this flow of air is cut off, and the air below the piston finally escapes by the exhaust port H. The air in the upper part of the cylinder is now pushing against the smaller end of the piston and also flows through a tube connecting the

openings I and K to press against the upper part of the head of the piston F. This flow continues as long as the reduced part of the piston at M is opposite K. The piston now descends with great velocity and strikes the anvil N which is in contact with the "steel" which ends in O. The air above the head of the piston then exhausts through H. The action repeats many times per second as long as the trigger is kept pressed. The tube L is a compression chamber and P is the retainer which keeps the steel from dropping out of the breaker.

By means of a blast of sand, projected by a jet of air, castings and also discoloured stone and brick walls are cleaned. Figures on glass and stone are engraved in this way. Tubes for transmitting letters or telegrams, or for carrying cash in our large retail stores, are operated by compressed air. It is used also for spraying trees, for spray-painting and for many other purposes which cannot be mentioned here.

Question.—Could steam under high pressure be used in the pneumatic drill and other compressed-air tools? State the advantages of air.

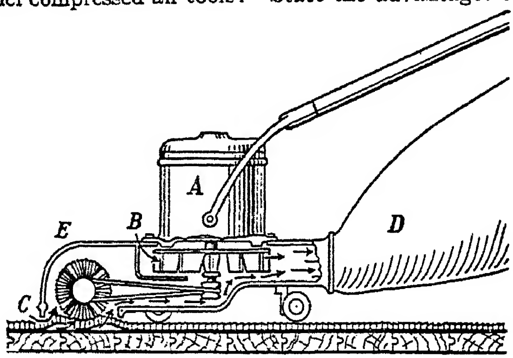


FIG. 82.—The vacuum cleaner.

79. Vacuum Appliances. The vacuum cleaner (Fig. 82) is an extremely useful practical application of air currents. The electric motor A drives the fan B which produces a partial vacuum, causing a current of air to flow in through the opening C. If the opening is placed against a carpet the air rushing in through the carpet carries with it dust and other dirt. This dirt-laden air is driven by the fan into the bag D, where the dirt is trapped, while the air passes out through the cloth. The rotating brush assists by loosening the dirt.

The vacuum brake is sometimes used on heavy motor trucks and buses. Its construction is somewhat similar to the compressed air brake (Fig. 76) but the piston is actuated by producing a vacuum on one side of the piston. The normal air pressure on the other side then moves the piston and sets the brakes.

In sugar refineries vacuum pumps are used to create a partial vacuum over the sugar solution which is being evaporated by heating. The reduced pressure allows the solution to boil at a lower temperature and scorching is avoided.

The milking machine is another useful application of the vacuum pump.

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Edward Ellsberg, *On the Bottom*.
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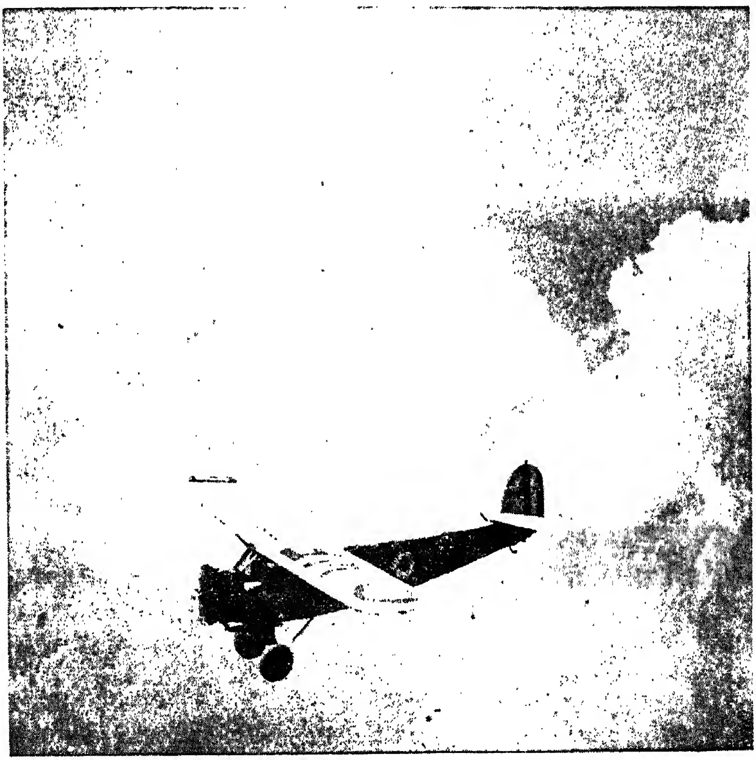


ROYAL CANADIAN AIR FORCE PLANE
Flying at a height of 12,000 feet.

CHAPTER XIV

WATER PUMPS AND WATER POWER

80. Water Pumps. From very early times pumps were employed for raising water from reservoirs, or for forcing it through tubes. It is certain that the suction pump was in use in the time of Aristotle (born 384 B.C.). The force-pump was probably the invention of Ctesibius, a mechanician who flourished in Alexandria in the second century B.C. To Ctesibius is also attributed the ancient fire-engine, which consisted of two connected force-pumps, spraying alternately.

81. Suction or Lift-pump. The construction of the common suction-pump is shown in Fig. 83. During the first strokes the suction-pump acts as an air-pump, withdrawing the air from the suction pipe BC (§ 68). As the air below the piston is removed, its pressure is lessened, and the pressure of the air on the surface of the water outside forces the water up the suction pipe and through the valve V_1 into the barrel. On the down-stroke the water held in the barrel by the valve V_1 passes up through the valve V_2, and on the next upstroke it is lifted up and discharged through the spout G, while more water is forced up through the valve V_1 into the barrel by the external pressure of the atmosphere. It is evident that the maximum height to which water, under perfect conditions,

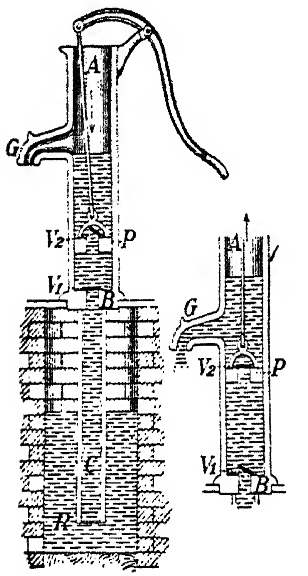


FIG. 83.—Suction-pump. AB, cylindrical barrel; BC, suction-pipe; P, piston; V_1 and V_2, valves opening upwards; R, reservoir from which water is to be lifted.

is raised by the pressure of the atmosphere cannot be greater than the height of the water column which the air will support. Taking the relative density of mercury as 13·6 and the height of the mercury barometer as 30 inches, this height would be $\frac{30}{12} \times 13 \cdot 6 = 34$ feet. But an ordinary suction-pump will not work satisfactorily if the piston is more than 25 feet above the surface of the water in the well.

82. Force-pump. When it is necessary to raise water to a considerable height, or to drive it with force through a nozzle, as for extinguishing fire, a force-pump is used. Fig. 84 shows a common form of its construction. On the up-stroke a partial vacuum is formed in the barrel, and the air in the suction tube expands and passes up through the valve V_1. As the plunger is pushed down, the air is forced out through the valve V_2. The pump, therefore, during the first strokes acts as an air-pump. As in the suction pump, the water is forced up into the suction-pipe by the pressure of the air on the surface of the water in the reservoir. When it enters the barrel, it is forced by the plunger at each down-stroke through the valve V_2 into the discharge pipe. The flow will obviously be intermittent, as the outflow takes place only when the plunger is descending. To produce a continuous stream, and to lessen the shock on the pipe, an air chamber F is often inserted in the discharge pipe. When the water enters this chamber, it rises above the outlet G which is some-

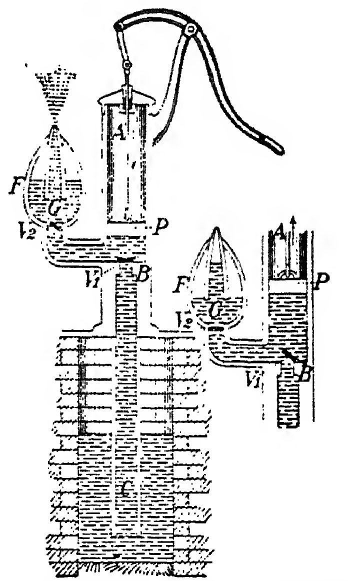


FIG. 84.—Force-pump. AB, cylindrical barrel; BC, suction-pipe; P, piston; F, air chamber; V_1, valve in suction-pipe; V_2 valve in outlet pipe; G, discharge pipe.

what smaller than the inlet, and compresses the air in the chamber. As the plunger is ascending, the pressure of the inclosed air forces the water out of the chamber in a continuous stream.

83. Double-action Force-pump. In Fig. 85 is shown the construction of the double-action force-pump. When the piston is moved forward to the right, in the direction of the arrow, water flows into the back of the cylinder through the valve V_1, while the water in front of the piston is forced out through the valve V_3. On the backward stroke water flows in through the valve V_2 and is forced out through the valve V_4. Pumps of this type are used in fire engines, or for any purposes for which a large continuous stream of water is required. They are usually worked by steam or other motive power.

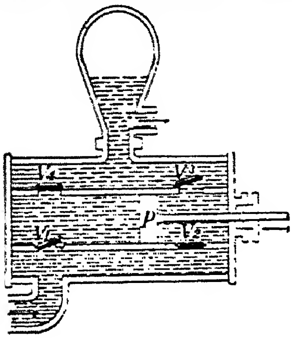


FIG. 85.—Double-action force-pump. P, piston; V_1, V_2, inlet valves; V_3, V_4, outlet valves.

QUESTIONS AND PROBLEMS

1. The capacity of the receiver of an air-pump is twice that of the cylinder; what fractional part of the original air will be left in the receiver after (*a*) the first stroke, (*b*) the third stroke?

2. The capacity of the cylinder of an air pump is one-fourth that of the receiver; compare the density of the air in the receiver after the first stroke with the density at first.

3. The capacity of the receiver of an air compressor is ten times that of the cylinder; compare the density of the air in the receiver after the fifth stroke with its density at first.

4. How high can alcohol be raised by a lift-pump when the mercury barometer stands at 760 mm. if the specific gravities of alcohol and mercury are 0·8 and 13·6 respectively?

5. Connect a glass model pump with a flask, as shown in Fig. 86. Fill the flask (*a*) full, (*b*) partially full of water, and endeavour to pump the water. Account for the result in each case.

6. Make a diagram to show how water can be raised from a well one hundred feet deep.

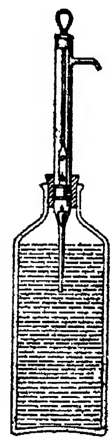


FIG. 86.

84. Siphon. If a bent tube is filled with water, placed in a vessel of water and the ends unstopped, the water will flow freely from the tube, so long as there is a difference in level in the water in the two vessels. A bent tube of this kind, used to transfer a liquid from one vessel to a lower level in another, is called a siphon.

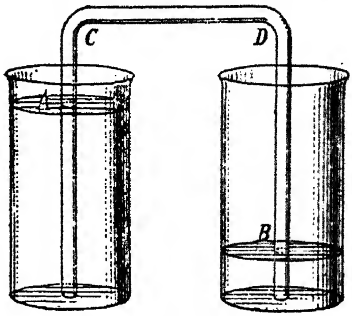


FIG. 87.—The siphon.

To understand the cause of the flow consider Fig. 87.

The pressure at A tending to move the water in the siphon in the direction AC

= the atmospheric pressure − the pressure due to the weight of the water in AC;

and the pressure at B tending to move the water in the siphon in the direction BD

= the atmospheric pressure − the pressure due to the weight of the water in BD.

But since the atmospheric pressure is the same in both cases, and the pressure due to the weight of the water in AC is less than that due to the weight of the water in BD, the force tending to move the water in the direction AC is greater than the force tending to move it in the direction BD; consequently, a flow takes place in the direction $ACDB$. This will continue until the vessel from which the water flows is empty, or until the water is at the same level in both vessels.

QUESTIONS AND PROBLEMS

1. Upon what does the limit of the height to which a liquid can be raised in a siphon depend? If the siphon were carried to the top of a mountain, how would its action be affected?

2. Over what height can (*a*) mercury, (*b*) water, be made to flow in a siphon?

3. How high can sulphuric acid be raised in a siphon when the mercury barometer stands at 29 in., taking the specific gravities of sulphuric acid and mercury as 1·8 and 13·6 respectively?

4. Upon what does the rapidity of flow in the siphon depend?

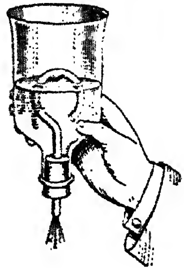


Fig. 88.

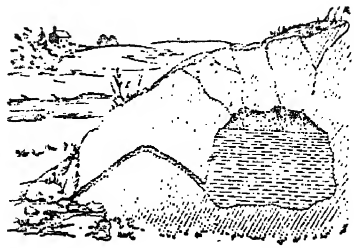


Fig. 89.—An intermittent spring.

5. Arrange apparatus as shown in Fig. 88. Let water from a tap run *slowly* into the bottle. What takes place? Explain.

6. Natural reservoirs are sometimes found in the earth, from which the water can run by natural siphons faster than it flows into them from above (Fig. 89). Explain why the discharge through the siphon is intermittent.

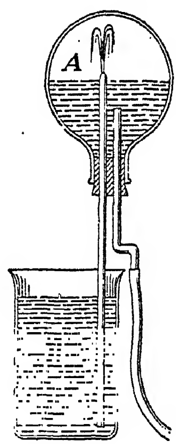


Fig. 90.

7. Arrange apparatus as shown in Fig. 90. Fill the flask *A* partly full of water, insert the cork, and then invert, placing the straight tube in the water as illustrated. Explain the cause of the phenomenon observed.

8. You are given a glass U-tube, a rubber tube and a vessel containing water and are asked to measure the pressure of illuminating gas at a gas-burner. How would you do it? What effect will the size of the tube have on the measurement?

9. Find the pressure (in pd. per sq. in.) upon a diver's suit at a depth of 72 feet in fresh water; also in salt water of specific gravity 1·025.

10. A person blows into a rubber tube attached to a U-tube containing water and is able to cause a difference in level of the water in the two tubes of 60 cm. Calculate the pressure per sq. cm. which he can exert.

85. Water in Motion. From early times men have used water-wheels to transform the energy of falling and running water into useful work. Many forms have been invented, the most modern and most efficient being the *Impulse* or *Pelton Wheel* and the *Reaction Turbine.*

86. Impulse Wheel. Pelton wheels are generally used where the fall of water is very great, say 1000 feet or more. A simplified diagram of a wheel of this type is shown in Fig. 91. The water under high pressure enters by the pipe *P* and flows through the nozzle *N* with great velocity. This jet of water strikes the concave buckets attached to the wheel *W* and causes it to rotate at a high speed. After transferring its energy to the wheel, the water escapes by the tail-race *T*.

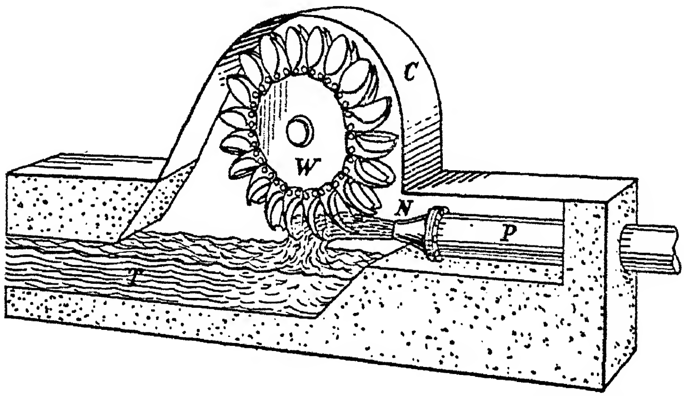


FIG. 91.—Pelton water-wheel. The front of the case *C* has been removed to show the wheel.

Impulse wheels may have diameters as great as 15 feet and a wheel using a single jet may develop 15,000 or more horsepower.

The small water-motors used for driving washing-machines and other household appliances are impulse wheels.

87. Reaction Turbine. This type of water-wheel is now being almost universally installed in large power plants where only a moderate head of water is available. Some of the finest examples are to be found in the neighbourhood of Niagara Falls, among the largest being those of the Hydro-Electric Power Commission of Ontario.

Fig. 92 shows the general arrangement of the Commission's power plant at Queenston. Water from the Niagara

River several miles above the Falls is conducted by a canal 13 miles long to the top of the cliff at Queenston where it is delivered through a steel penstock *A* to the 60,000 horse power turbine *B* which is directly connected by a vertical shaft 30 inches in diameter, to the 45,000 kilovolt-ampere generator *C* immediately above it. The electricity is generated at a pressure of 12,000 volts and is "stepped up" to a pressure of 110,000 volts by the transformer *D* from which leads off the transmission line *E*.

The water after passing through the wheel drops through the draft-tube *F* and escapes to the river by the tail-race *G*.

In Fig. 93 is shown a horizontal section of the turbine. The water from the penstock is delivered into the spiral-case *A*, from which it passes through a series of adjustable guide vanes *B*, which regulate

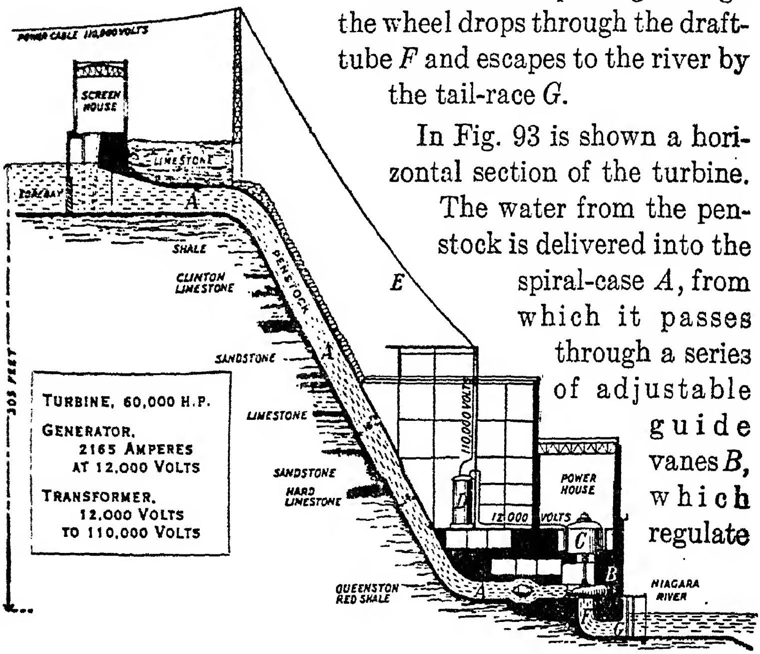


FIG. 92.—Arrangement of Hydro-Electric power plant at Queenston.

the inward flow of the water and also direct it against the blades of the "runner" *C* in a direction best adapted to produce rotation. *D* is the shaft of the runner. The water moves through the runner inwards and downwards and the blades are curved to take advantage of both motions. On

leaving the runner the water passes out through the draft-tube into the tail-race.

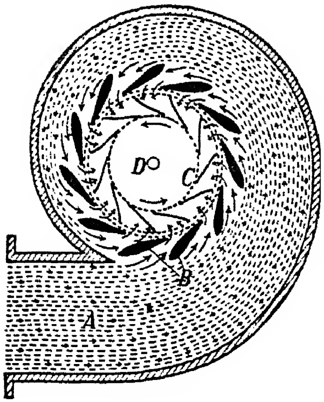


FIG. 93.—Horizontal section through the turbine showing spiral-case *A*, guide vanes *B* and runner *C*.

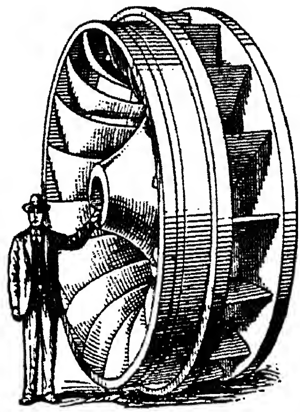
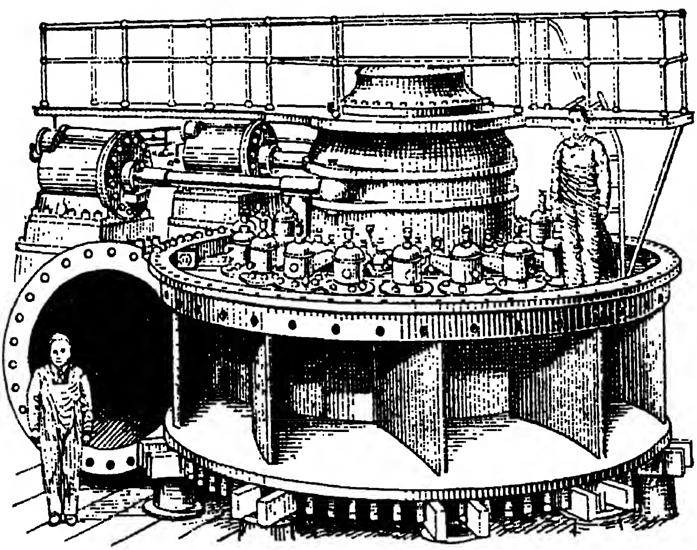


FIG. 95.—The runner or rotating part of the turbine. Note its great size and the curvature of the blades.

Figure 94 shows the guide vanes and the mechanism by which they are controlled. Fig. 95 gives a good idea of



.—Part of the spiral case is removed showing the guide vanes. The mechanism for controlling them is seen above.

the enormous size of the runner and also shows how the blades are curved. The runner is of cast steel. Its outside diameter is 10 ft. 5 in., its weight is 42,000 pounds. and it rotates 187½ times per minute. The power house at Queenston contains 10 turbines similar to the one just described, developing a total of nearly 600,000 horsepower. An outer view of the power-house is shown in the adjoining plate, while a view of the interior of the house is given in plate 31, facing page 576 and a brief description of the generators is given in § 576.

REFERENCES FOR FURTHER INFORMATION

R. W. Angus, *Hydraulics for Engineers.*
R. L. Daugherty, *Hydraulics.*
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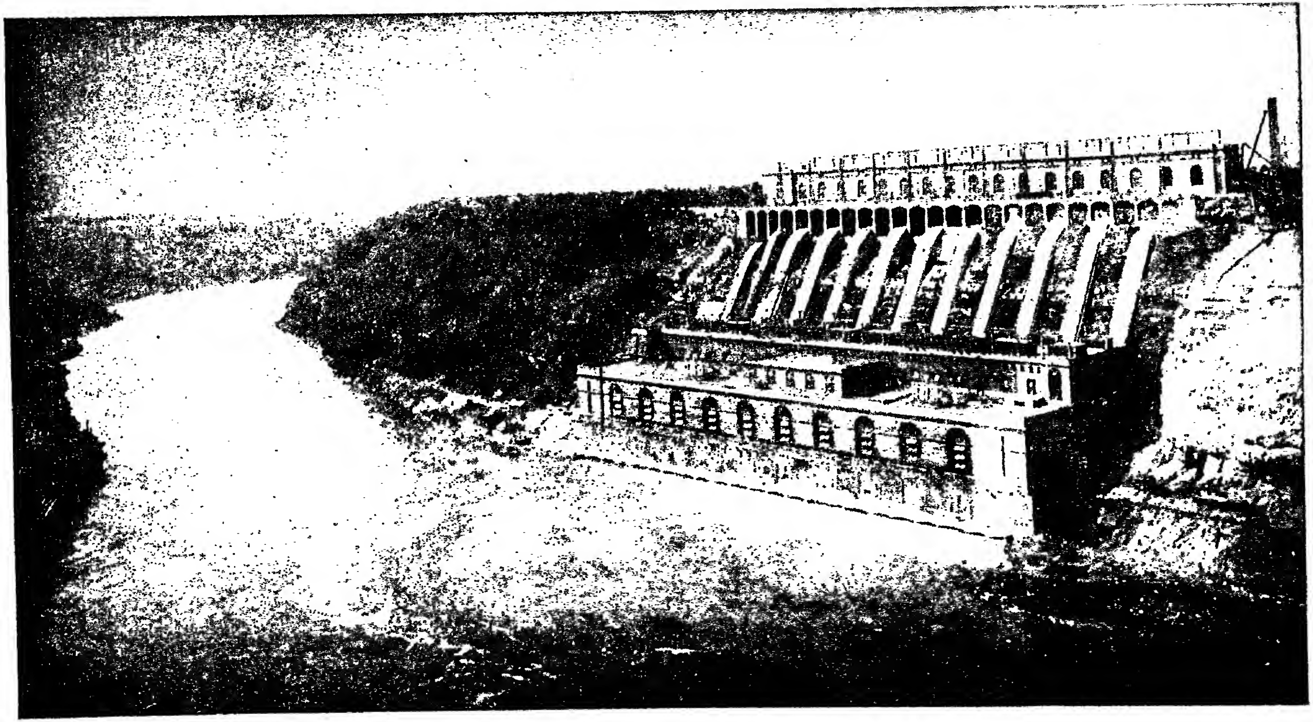
Encyclopedia Britannica, Articles on Water Turbines and Pumps.



THE ONTARIO HYDRO-ELECTRIC COMMISSION QUEENSTON PLANT

• **Plate 7**

This is the largest power house of the Hydro-Electric Power Commission of Ontario. It contains ten turbines developing about 60,000 h.p. each, directly driving the generators above them. The interior of the power house is shown in Plate 31 facing page 576.

(Photograph supplied by the Power Commission)

PART III—MECHANICS OF SOLIDS

CHAPTER XV

VELOCITY, ACCELERATION

88. Rest and Motion. When we look about we naturally divide the things we see into two classes—those at rest and those in motion. The houses, the fences and the trees are at rest, while the motor-cars on the road, the railway-train in the distance and the birds flying over the field we declare to be in motion.

But a little thought will show that this classification of bodies is not so simple as it appears at first sight, that indeed a body considered from one point of view may be at rest, while from another it may be in motion. For instance, a passenger on a railway-train is at rest with respect to a fellow-traveller, but with respect to a third person on the ground outside they are both in motion. It is impossible to think of a body at rest which, when looked at in another way, would not be considered to be in motion. Thus motion is quite as natural a state as rest.

89. Velocity or Speed. A body is in motion when it is changing its position relative to another which we take to be at rest, and the change of position we call its displacement. Now along with the displacemet which a body undergoes we generally consider the time required to produce it. Indeed, that is frequently of the utmost importance. In the case of a serious accident it is essential that the injured ones should not simply be given a "displacement" from the scene of the accident to the hospital, but that it be done in as short a time

as possible—in other words, that the conveyance carrying them shall travel with great speed or velocity. (No distinction will be made between these two terms.)

Velocity is the rate of change of position, or, in other words, **the time-rate of displacement.**

If a train goes from Toronto to Montreal, a distance of 330 miles, in 10 hours, the average velocity = 330 ÷ 10 = 33 miles per hour. Sometimes the speed is greater and sometimes less than this, but this is the average.

$$\text{Average velocity} = \frac{\text{Space}}{\text{Time}},$$

or $\quad \text{Space} = \text{Average velocity} \times \text{Time}.$

On a stretch of level track the train may travel with approximately uniform velocity, but in motions met with in nature there are few velocities which may be considered absolutely uniform.

The word *knot*, used in stating the speed of a ship, includes in itself both the ideas of distance and time. A speed of 20 knots means 20 nautical miles per hour. A nautical mile is the length of 1′ or $\frac{1}{60}°$ of a great circle on the earth considered to be a sphere, and is given as 6080 feet. This is very nearly $1\frac{1}{6}$ statute, or ordinary, miles. Hence a ship making 30 knots is travelling at approximately 35 miles per hour.

PROBLEMS

1. An ambulance goes 8 mi. in 20 min.; find the average speed in mi. per hr.

2. A train leaves Winnipeg at 10.40 p.m. and reaches Regina next morning at 9.40 as shown by the same time-piece. The distance is 357 miles. Find the average speed.

3. A train leaves Montreal at 9.45 p.m. Monday and reaches Vancouver on Saturday at 9.10 a.m., Pacific time, which is 3 hours slow of Montreal, or Eastern, time. The average speed, including stops, was $26\frac{1}{4}$ mi. per hr. Find the distance.

4. Find the equivalent, in ft. per sec., of a speed of 60 mi. per hr.

5. An eagle flies at the rate of 30 metres per sec.; find the speed in km. per hr.

6. A sledge party in the Arctic regions travels northward on the ice, for ten successive days, 10, 12, 9, 16, 4, 15, 8, 16, 13, 7 miles, respectively. Find the average velocity.

7. If at the same time the ice on which the party is travelling is drifting southward at the rate of 10 yd. per min., find the average velocity northward.

8. A train travels at an average speed of 60 mi. per hr. on a 240-mile trip between two stations, while the return trip is made at the rate of 40 mi. per hr. calculate the average speed for the round trip.

9. The speed of a street car averages 22 ft. per sec. How far will it go in 3 hours?

10. The armature of a dynamo is 3 metres in diameter, and it revolves 150 times per min. Find the speed of a point on its circumference.

11. Light travels at the rate of 186,000 mi. per sec., and it takes 8·67 years to come from Sirius, the Dog Star, to us. Find the distance of Sirius.

90. Accelerated Motion. A person is not afraid to jump from a verandah to the ground, but hesitates to do so from the top of a high fence, and he would simply refuse to leap from an upstairs window unless to save his life. The reason is obvious enough. The greater the distance a body falls through the air, the faster it moves, and in falling only a few feet a person may acquire a velocity great enough to injure him when he strikes the ground.

On going down a grade on a railway, even though the engineer shuts off the steam, the train continually gains in speed and the brakes may have to be set in order to observe the instruction "safety first." If a stone is thrown upward its velocity gradually diminishes until the stone stops and it then comes downward with continually increasing velocity.

When the velocity of a body is changing, the motion is said to be **accelerated.** If the velocity is diminishing we more often say that the motion is retarded, but a retardation may be considered a negative acceleration.

. **How Acceleration is Expressed.** We are all familiar the term acceleration as used in connection with the velocity of an automobile.

Let us suppose that at a given instant the speedometer of a car (Fig. 96) reads 10 miles per hour and that by pressing the accelerator we succeed in making the speedometer read 25 miles per hour at the end of 5 seconds. Then the increase in velocity is 15 miles per hour and that increase is gained in 5 seconds. Let us assume that the increase in the velocity, or the acceleration, is uniform. Then we may say that a gain of

15 miles per hour in 5 sec.
= 3 miles per hour in 1 sec.
= 4·4 ft. per sec. per sec.

Similarly a gain of

30 km. per hour in 10 sec.
= 3000 m. per hour in 1 sec.
= 50 m. per min. per sec.

Beginners sometimes have difficulty with the two time phrases (per sec., per sec.) but the difficulty clears up when it is realized that in expressing an acceleration we must state how much the velocity changes in unit time.

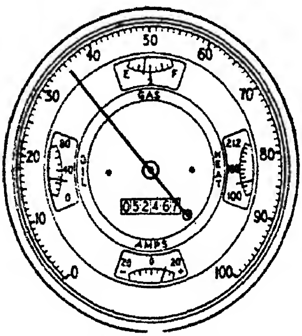


Fig. 96.—Speedometer.

Acceleration is rate of change of velocity.

PROBLEMS

1. A train leaving a station has a uniform acceleration of 2 ft. per sec. per sec. What will be its velocity at the end of the 10th sec.? At the end of 15 sec.?

2. If the acceleration of a street-car is 2 ft. per sec. per sec., how many sec. will it take to acquire a speed of 30 mi. per hr.?

3. An automobile going at the rate of 40 mi. per hr. is brought to rest in 10 sec. Find the acceleration (retardation) if the decrease in velocity is uniform.

4. A bicyclist coasts down a hill with an acceleration of 0·5 m. per sec. per sec., and reaches the bottom in 10 sec. Find his velocity at the foot of the hill. If he then goes up the opposite hill and is brought to rest in 6 sec., what is the acceleration (retardation)?

5. A railway train changes its velocity uniformly in 2 min. from 20 km. an hr. to 30 km. an hr. Find the acceleration in cm. per sec. per sec.

6. A stone sliding on the ice at the rate of 200 yd. per min. is gradually brought to rest in 2 min. Find the acceleration in ft. and sec.

7. Change an acceleration of 981 cm. per sec. per sec. into ft. per sec. per sec. (See Table, opposite page 1.)

92. Displacement in Uniformly Accelerated Motion. Consider a body starting with an initial velocity of 12 cm. per sec. and moving with an acceleration of 5 cm. per sec. per sec.

In an interval of 4 seconds the increase in velocity

$$= 4 \times 5 = 20 \text{ cm. per sec.}$$

The velocity attained in 4 seconds

$$= 12 + 20 = 32 \text{ cm. per sec.}$$

The average velocity during the interval

$$= \tfrac{1}{2}\,(12 + 32) = 22 \text{ cm. per sec.}$$

The displacement s equals the average velocity $\times$ the time,

or $$s = 22 \times 4 = 88 \text{ cm.}$$

In general, for a body travelling with uniform acceleration, the final velocity v = the initial velocity u + the gain in velocity, i.e. for a time t and acceleration a

$$v = u + at.$$

Also, $$\text{average velocity} = \frac{\text{Initial velocity} + \text{Final velocity.}}{2}$$

The equation expressing the displacement in terms of the initial and final velocities is

$$t.$$

If the body starts from rest, $u = 0$ and $v = at$

Average velocity $= \tfrac{1}{2}(0 + at) = \tfrac{1}{2}\,at.$

Hence $$s = \tfrac{1}{2}at \times t = \tfrac{1}{2}\,at^2.$$

Also, since $$v = at,\ t = \frac{v}{a} \text{ and } s = \tfrac{1}{2}\,a \times \frac{v^2}{a^2}$$

or $$v^2 = 2as.$$

PROBLEMS

1. A train leaving a station has a uniform acceleration of 3 ft. per sec. per sec. Estimate the velocity attained in 30 sec. and the distance traversed during this interval.

2. A motor car in 5 min. increases its velocity uniformly from 24 to 60 mi. per hr. Estimate the distance travelled during the above interval. Calculate the acceleration in ft. per sec. per sec.

3. How far does a railway train go while increasing its speed uniformly in 4 min. from 30 to 50 mi. per hr.?

4. The acceleration of a street car is 2 ft. per sec. per sec.; calculate the distance travelled in acquiring, from rest, a speed of 30 mi. per hr.

5. A stone sliding on the ice at the rate of 200 metres per min. is gradually brought to rest in 4 min. How far does it go during this interval?

6. An automobile driver travelling at the rate of 30 mi. per hr. sees an excavation in the road 66 ft. ahead. He applies the brakes and the car stops just at the excavation. Find the acceleration (retardation).

(NOTE. Find the average velocity, then the time, then the acceleration.)

7. An avalanche slides down a mountain side with an acceleration of 6 ft. per sec. per sec. Calculate its velocity after it has descended from rest a distance of 400 yards.

8. A racing automobilist starts from rest on a level course and at the end of 2 mi. is going at the rate of 300 mi. per hr. (*a*) Find his acceleration, supposed uniform. (*b*) How long did he take to go the 2 mi.?

93. Motion under Gravity. The most familiar illustration of motion with uniform acceleration is a body falling freely. Suppose a stone to be dropped from a height. At once it acquires a velocity downward, which continually increases as it falls; and in a second or two it is moving so fast that the eye can hardly follow it.

The method which naturally suggests itself for determining the magnitude of the acceleration due to gravity is to time the fall of a body over a measured distance. For example, if we gradually increase the height from which a body is allowed to fall until at last it just reaches the ground in 1 second, we find the distance is about 16 feet.

We may employ one of the formulas in § 92.

We have $t = 1$, $s = 16$ and require a.

But $s = \frac{1}{2} at^2$;

$\therefore 16 = \frac{1}{2} a \times 1$, and $a = 32$ ft. per sec. per sec.

The acceleration due to gravity is usually denoted by the letter g and the most accurate method of measuring its value is by means of the pendulum. In this way it is found that

$$g = 32{\cdot}2 \text{ ft. per sec. per sec. (approx.)}$$
$$= 981 \text{ cm. per sec. per sec. (approx.)}$$

These values vary slightly with the position on the earth's surface. At the equator $g = 978{\cdot}10$; at the pole, $983{\cdot}11$; at Toronto, 980.6.

94. All Bodies falling freely have the same Acceleration. Galileo asserted that all bodies, if unimpeded, fall at the same rate. Now, common observation shows that a stone or a piece of iron, for instance, falls much faster than a piece of paper or a feather. This is explained by the fact that the paper or the feather is more impeded by the resistance of the air.

From the top of the Leaning Tower of Pisa (see § 135), Galileo allowed balls made of various materials to fall, and he showed that they fell in practically the same time. Sixty years later, when the air-pump had been invented, the statement regarding the resistance of the air was verified in the following way. A coin and a feather were placed in a tube (Fig. 97) four or five feet long and the air was exhausted. Then, on inverting the tube, it was found that the two fell to the other end together. The more completely the air is removed from the tube, the closer together do they fall.

If a "guinea and feather" tube (Fig. 97) is not available the following simple experiment may be performed:

Cut a paper disc slightly smaller than a quarter of a dollar, place it on the quarter and hold the coin between the thumb and forefinger, with its flat face horizontal. On releasing it the coin and the paper disc fall to the ground at the same rate. Here the falling coin prevents the air resistance from acting on the paper, and the true effect due to gravity is obtained.

Fig. 97.—Tube to show that a coin and a feather fall in a vacuum with the same acceleration.

Instead of using a disc of paper the paper may simply be rolled into a small ball and allowed to fall alongside the coin.

95. Bodies Falling Freely. Suppose a ball is thrown vertically upward. Its velocity gradually decreases until at last it comes to rest. Then as it falls it regains the velocities which it had on its upward path, and it ends with the same speed with which it started up. The time to come down is the same as to go up; and the speed at any point of its path is the same coming down as it was going up.

Example.—Let the ball be thrown upwards with a velocity of 19·6 m., or 1960 cm., per sec. At the end of 1 sec. its velocity will be reduced 980 cm. per sec.; at the end of the 2nd sec. it will be 1960 cm. per sec. less, that is, it will be reduced to zero. Hence the ball will rise 2 sec. It will now fall for 2 sec., at the end of the 1st sec. having a velocity of 980 cm. per sec., and at the end of the 2nd sec. 1960 cm. per sec.

Going up the ball loses 980 cm. per sec. of its velocity every second, and coming down it regains that amount.

If the velocity of the ball upward had been 1000 cm. per sec. it would have risen for $1000 \div 980 = 1{\cdot}02$ sec., and then it would fall for 1·02 sec.

In this case the average velocity upward $= \frac{1}{2}(0 + 1000) = 500$ cm. per sec., and the space traversed $= 500 \times 1{\cdot}02 = 510$ cm. (approx.).

In this example the resistance of the air is neglected.

PROBLEMS

(Unless otherwise stated, take as the measure of the acceleration of gravity, with centimetres and seconds, 980; with feet and seconds, 32.)

1. A stone was dropped from a high bridge to the river below and was observed to strike the water 3 seconds later. The height of the bridge above the river was 44·1 metres. Find the value of g in cm. per sec. per sec.

If you were performing this experiment how would you measure the time and the height?

2. A body falls freely for 6 seconds. Find the velocity at the end of that time, and the space passed over in British units.

3. What initial speed upward must be given to a body that it may rise for 4 seconds?

4. The Eiffel Tower is 300 metres high, and the tower of the City Hall, Toronto, is 305 ft. high. How long will a body take to fall from the top of each tower to the earth?

5. On the moon the acceleration of gravity is approximately one-sixth that on the earth. If on the moon a body were thrown vertically upward

with a velocity of 90 ft. per sec., how high would it rise, and how long would it take to return to its point of projection?

6. A body is projected vertically upward with a velocity of 39·2 metres per sec. Find (1) how long it will continue to rise; (2) how high it will rise.

7. A stone is dropped down a deep mine, and one second later another stone is dropped from the same point. How far apart will the two stones be after the first one has been falling 5 seconds?

8. A stone is projected vertically upward and returns to the ground in 10 sec. Find (1) the velocity of projection, (2) the height to which it rises, (3) its height above the ground after 1, 2, 3, 4, 5 sec., respectively.

CHAPTER XVI

COMPOSITION OF VELOCITIES; TRANSLATION AND ROTATION

96. Composition of Velocities. Suppose a passenger to be travelling on a railway train which is moving on a straight track at the rate of 15 miles per hour, or 22 feet per second. While sitting quietly in his seat, he has a motion, in the direction of the track, of 22 feet per second.

Next, let the passenger rise and move directly across the car, going a distance of 6 feet in 2 seconds. His velocity across will be 3 feet per second.

In Fig. 98 A is the position of the passenger at first. If the train were at rest, in 2 seconds he would move from A to

FIG. 98.—Motion of a passenger walking across a moving railway car.

C, 6 feet; while, if he sat still, the train in its motion would carry him from A to B in 2 seconds, a distance of 44 feet. It is evident, then, that if the train move forward and the passenger move across at the same time, at the end of 2 seconds he will be at D, *i.e.*, 44 feet forward and 6 feet across.

Moreover, at the end of 1 second, he will be 22 feet forward and 3 feet across, that is, halfway from A to D. The motions which he has will carry him along the line AD in 2 seconds.

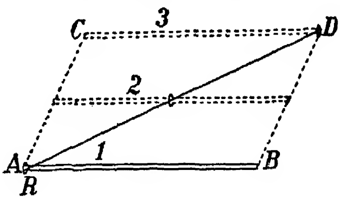


FIG. 99.—Showing how to add together two motions of a ring on a rod.

97. Law of Composition. Another example will perhaps make clearer this principle of compounding velocities.

Let a ring R (Fig. 99) slide with uniform velocity along a smooth rod AB, moving from A to B in 1 second. At the

same time let the rod be moved in the direction AC and BD with a uniform velocity, reaching the position CD in a second. The ring will be at D at the end of a second.

At the end of half a second from the beginning the ring will be half-way along the rod, and the rod will be in position (2) half-way between AB and CD. It is evident that between the two motions the ring will move uniformly along the line AD, travelling this distance in 1 second.

From these illustrations we can at once deduce the law of composition of velocities.

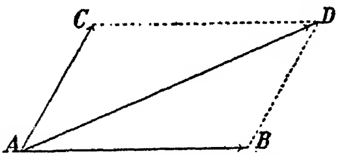


FIG. 100.—The parallelogram of velocities.

Let a particle possess two velocities simultaneously, one represented in direction and magnitude by the line AB, the other by AC. (Fig. 100). Complete the parallelogram $ABDC$. Then the diagonal AD will represent in magnitude and direction the resultant velocity.

PROBLEMS

1. Suppose a vessel to steam directly east at a velocity of 12 mi. per hr., while a north wind drifts it southward at a velocity of 5 mi. per hr. Find the resultant velocity.

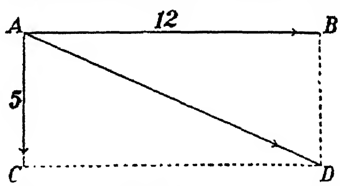


FIG. 101.—Illustrating the motion of a vessel.

Draw a line AB, 12 cm. long, to represent the first component velocity; and AC, 5 cm. long, to represent the second. (Fig. 101).

Completing the parallelogram, which in this case is a rectangle, AD will represent the resultant velocity.

Here we have $AD^2 = AB^2 + BD^2 = 12^2 + 5^2 = 169 = 13^2$.

Hence $AD = 13$, *i.e.*, the resultant velocity is 13 mi. per hr. in the direction represented by AD.

2. A ship moves east at the rate of $7\frac{1}{2}$ mi. per hr., and a passenger walks on the deck at the rate of 3 ft. per sec. Find his velocity relative to the earth in the following three cases: (1) when he walks toward the bow, (2) toward the stern, (3) across the deck.

3. A ship sails east at the rate of 10 mi. per hr., and a north-west wind drives it south-east at the rate of 3 mi. per hr. Find the resultant velocity.

To calculate the resultant accurately requires a simple application of trigonometry, but the question can be solved approximately by drawing a careful diagram. Draw a line in the easterly direction 10 in. long, and lay off from this, by means of a protractor, a line in the south-east direction, 3 in. long. Complete the parallelogram and measure carefully the length of the diagonal. (12·30 mi. per hr.).

4. Find the resultant of two velocities, 20 cm. per sec. and 50 cm. per sec. (*a*) at an angle of 60°, (*b*) at an angle of 30°. (Carefully draw diagrams, and measure the diagonals.)

5. A particle has three velocities given to it, namely, 3 ft. per sec. in the north direction, 4 ft. per sec. in the east direction, and 5 ft. per sec. in the south-east direction. Find the resultant. (Carefully draw a diagram.)

6. A ship is steaming eastward at 15 mi. per hr. and a wind blows from the north at 20 mi. per hr. By means of a diagram show the direction the smoke from the funnel takes and find its velocity with respect to the water which is supposed to be at rest.

7. When a motor car is standing still the drops of rain are seen to fall vertically, but when it is moving forward at 30 mi. per hr. the rain, to a person in the car looking to right or to left, appears to be falling in a direction making 30° with the vertical. Draw a diagram to explain how this takes place, and from it calculate the velocity of the falling drops.

8. A river is 440 yd. wide and flows at the rate of 3 mi. per hr. A man can row (for a time) at the rate of 5 mi. per hr. and he wishes to go from a point A on one side to a point B directly opposite.

(*a*) He rows across with his boat always at right angles to the flow of the current. Draw a diagram to show where he will land, and calculate how far it will be from B. Also find how long he takes to cross.

(*b*) By means of another diagram show in what direction he must point his boat in order to land at B. How long will it take to cross?

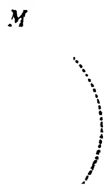


Fig. 102.—Motion in a circle.

98. Motion in a Circle. Let a body M (Fig. 102) be made to revolve uniformly in a circle with centre O and radius r. A familiar illustration of this motion is seen when a stone at the end of a string is whirled about.

In this case the length of the line MO does not alter, and yet M has a velocity with respect to O. This arises from the continual change in the direction of the line MO. Every time the body describes a circle, the line changes its direction through 360°.

If the string were cut and M were thus allowed to continue with the velocity it possessed, it would move off in the tangent to the circle MT. This effect is well illustrated by the drops of water flying from the wheels of a bicycle, or the sparks from a rapidly rotating emery wheel.

We see, then, that *one point has a velocity with respect to another when the line joining them changes in magnitude or direction.*

99. Translation and Rotation. If a body move so that all points in it have the same speed in the same direction, we say that it has a motion of translation (Fig. 103). Examples: the car of an elevator, or the piston of an engine.

FIG. 103.—Showing motion of translation.

If, however, a body move so that all points in it move in circles having as centre a point called the centre of mass, or centre of gravity*, the motion is a pure rotation (Fig. 104). Example: a wheel on a shaft, such as the wheel of a sewing-machine or a fly-wheel.

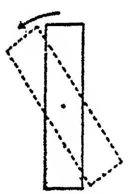


FIG. 104.—Showing motion of rotation.

Usually, however, both motions are present, that is, the body has both translation and rotation. Examples: the motions of the planets, of a carriage wheel, of a body thrown up in the air.

If a body is rotating about an axis through a point O in it, it is evident that those points which are near O, such as P, Q (Fig. 105), have smaller speeds than have those points such as R, S, which are farther away.

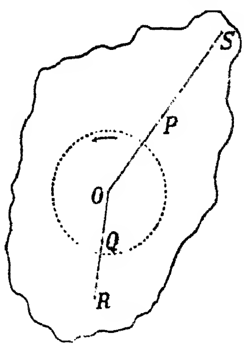


FIG. 105.—In a rotating body all points have the same angular velocity.

But they all describe circles about O in the same time and hence their angular velocities are all equal. They all turn the same number of degrees per second.

*Explained in Chapter XXI.

CHAPTER XVII

INERTIA, MOMENTUM, FORCE

100. Mass, Inertia. The *mass* of a body has been defined (§ 14) as the quantity of matter in it. Just what *matter* is, no one can say. We all understand it in a general way, but we cannot explain it in terms simpler than itself. We must obtain our knowledge regarding it by experience.

When we see a boy kick a football high into the air, we know that there is not much matter in it. If it were filled with water or sand, so rapid a motion could not be given to it so easily, nor would it be stopped or caught so easily on coming down. A cannon-ball of the same size as the foot-ball and moving with the same speed, would simply plough through all the players on an athletic field before it would be brought to rest.

To a person accustomed to handling a utensil made of iron or enamelled ware, one made of aluminium seems singularly easy to move. If a thin rubber ball is thrown at you with great speed, you catch it with ease; if it is a base-ball, it requires a much greater effort to stop it; while if it is an iron ball, you had better let it alone.

All our experience teaches us that it requires an effort to put in motion matter which is at rest or to bring to rest matter which is in motion; or, in other words, **all matter has inertia.**

Further, the greatness of the effort which must be exerted to put a body in motion or to bring it to rest is proportional to its mass; or, **the inertia of a body is proportional to its mass.**

101. Newton's Laws of Motion: the First Law. In the preceding section we have used the word "effort" a number of times when speaking of putting a body in motion or of

bringing it to rest. In physics the word which is used with this meaning is force. In 1687 Sir Isaac Newton published his "Principia,"* in which he gave his three famous *Laws of Motion.* The First Law is simply a statement of the conclusion which we have just arrived at, but expressed in a form which has never since been improved upon. It is as follows:

Every body continues in its state of rest, or of uniform motion in a straight line, unless it be compelled by external force to change that state.

This is often referred to as the *Law of Inertia.*

102. Illustrations of the First Law. A ball lying at rest on the grass will not move itself. If, however, it is rolled on the grass, it 'slows up' and comes to rest. If we roll it on a smooth pavement, the motion persists longer, and if on smooth ice, longer still. It is seen that as we remove the external force (of friction), and leave the body more and more to itself the motion continues longer, and we are led to believe that if there were no friction, it would continue uniformly in a straight line.

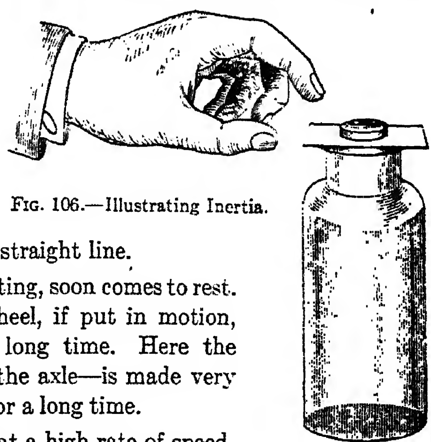


FIG. 106.—Illustrating Inertia.

An ordinary wheel, if set rotating, soon comes to rest. But a well-adjusted bicycle wheel, if put in motion, will continue to move for a long time. Here the external force—the friction at the axle—is made very small, and the motion persists for a long time.

When a locomotive, running at a high rate of speed, leaves the rails and is rapidly brought to a standstill, the cars behind do not immediately stop, but continue ploughing ahead, and usually do great damage before coming to rest.

If one wishes to jump over a ditch, he takes a run, leaps up into the air, and his body, persisting in its motion, reaches the other side.

In an earthquake the buildings tend to remain at rest while the earth shakes under them, and they are broken and crumble down.

*The full title of the book is "Principia Mathematica Naturalis Philosophiae", *i.e.*, "The Mathematical Principles of Natural Philosophy."

Lay a card over the mouth of a bottle and place a small coin on the card. (Fig. 106). On 'flipping' the card suddenly with the finger it is driven out, while the coin, owing to its inertia, remains behind and drops into the bottle.

The hydraulic ram is an interesting device for utilizing the inertia of a moving column of water. It consists of a reservoir A (Fig. 107) fed by a natural stream, and from this a pipe B of considerable length leads the

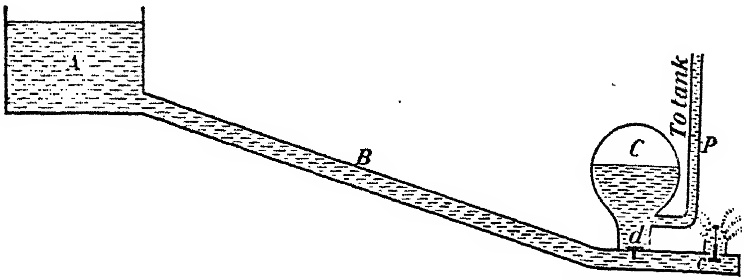


FIG. 107.—Principle of the hydraulic ram. Water is raised from A to a tank at a considerable height.

water to a lower level where it rushes against and closes a valve c. The inertia of the column carries it onward, and, pushing upward the valve d, some of the water enters the chamber C and thence goes into the pipe P, which runs up to a tank in the attic of a house or in some other elevated position. Immediately after coming to rest the water rebounds, and the valve c drops. This allows some water to escape, and the column starts moving in the pipe B again, and the operation is repeated. The pipe B should be comparatively long and straight. The greater part of the water escapes at c and is wasted, but a fall of (say) 4 feet can raise the remaining portion to a height of perhaps 30 feet. The actual appearance of a small hydraulic ram is shown in Fig. 108.

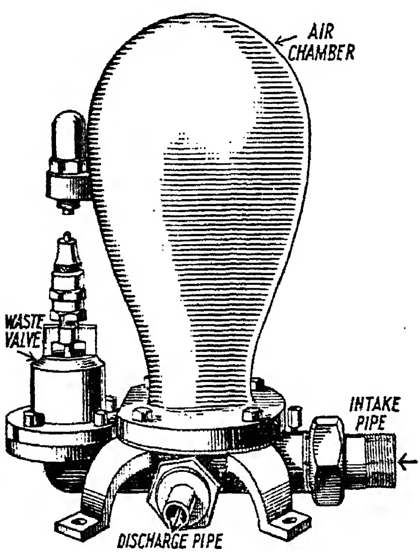


Fig. 108.—A hydraulic ram.

103. Momentum. Now from our experience we know that, in estimating the greatness of the force required to put a body in motion, we must take into account not only the mass of the body but also the velocity which is given to it. It requires a much greater force to impart a great velocity to a body than to give it a small one; and to stop a rapidly moving body is much harder than to stop one moving slowly. We feel that there is something which depends on both mass and velocity, and which we can think of as *quantity of motion*. This is known in physics as **momentum.** It is proportional to both the mass and the velocity of the body, thus

$$\textbf{Momentum} = \textbf{mass} \times \textbf{velocity} = mv,$$

where m is the mass of the body and v its velocity of translation.

PROBLEMS

1. Compare the momentum of a car weighing 1,800 kg. and moving with a velocity of 30 km. an hr. with that of a cannon ball weighing 20,000 gm. and moving with a velocity of 50,000 cm. per sec.

2. A man weighing 150 lb. and running with a velocity of 6 ft. per sec. collides with a boy of 80 lb. moving with a velocity of 9 ft. per sec. Compare the momenta.

3. Compare the momentum of a $1\frac{1}{2}$-oz. bullet fired with a velocity of 2800 ft. per sec. with that of a 2-lb. weight which has fallen freely for 2 sec.

104. How to Measure Force. Newton's Second Law. If there is a change in the condition of a body (*i.e.*, if it does not remain at rest or in uniform motion in a straight line), then there is a change in its momentum, that is, in the *quantity of motion* it possesses. Any such change is due to some external influence which is called **force,** and as a result of our experience we recognize that the amount of the change in a given length of time is proportional to the impressed force. Further, we recognize that the total change of momentum is also proportional to the length of time during which the

force acts. We know that a driver, wishing to stop a heavily-loaded truck, must apply the brakes for a longer time than when the truck is empty.

Again, a force must act in a definite direction, and the change in momentum must be in that direction.

Newton summed up these results of our experience in his **Second Law of Motion**, which is as follows:

Rate of change of momentum is proportional to the impressed force and takes place in the direction in which the force acts.

The word force is used, in ordinary conversation, with an almost endless number of meanings, but in physics the meaning is definite. If there is a change of momentum, force is acting. Sometimes, however, a body is not free to move. For instance, you may lift on a stone and produce no motion. In this case force would *tend* to produce momentum. We can include such cases by framing our definition thus:

Force is that which tends to change momentum.

It is to be observed that there is no suggestion as to the cause or source of force. Whatever the nature of the external influence on the body may be, we simply look at the effect; if there is a change of momentum, then it is due to force.

It is evident, also, that the total effect of a force depends upon the time it acts. Thus, suppose a certain force to act upon a body of mass m for 1 second, and let the velocity generated be v, *i.e.*, the momentum produced is mv. If the force continues for another second, it will generate additional velocity v, or $2v$ in all, and the momentum produced will be $2mv$; and so on.

Let us state this result in symbols. Let F represent the force, and t sec. be the time during which it acts. At the end of t sec. the force will have generated a certain momentum, which we may write mv.

Then Force $\times$ time = momentum produced, or $Ft = mv$.

$$\text{Hence } F = m\frac{v}{t} = ma, \text{ since } v = at \text{ (§ 92)},$$

that is

$$\text{Force} = \text{mass} \times \text{acceleration}.$$

105. Units of Force. We can fix our ideas regarding force by considering the attraction of the earth on a mass. A bit about 1 cm. long off the larger end of a chalk crayon contains about 1 gram-mass. On picking up a gram-mass we are conscious that there is a pull downwards tending to give it a velocity, that is, to change its momentum. This pull we call a *gram-force*; it is the attraction of the earth on a gram-mass on the earth's surface. In the same way the attraction of the earth on a pound-mass on its surface is a *pound-force.*

Next, allow the gram-mass to fall freely for 1 sec. At the end of the second it has a velocity of 980 cm. (32·2 ft.) per sec. Hence when a gram-force acts on a gram-mass for 1 sec. the momentum generated

$$= \text{mass} \times \text{velocity} = 1 \times 980 = 980 \text{ C.G.S. units.}$$

If the mass is 15 grams, the force acting on it is 15 grams-force, and the momentum generated in 1 sec.

$$= 15 \times 980 = 14{,}700 \text{ units; and so on.}$$

Now, as a body is raised above the surface of the earth, the force of attraction pulling it downward becomes smaller, as will be explained in Chapter XIX. Imagine a gram-mass to be carried further and further away until the attraction on it is only 1-980th of what it is at the surface of the earth, that is, the force up there is $\frac{1}{980}$ gram-force.

Then, if from this far-distant place the gram-mass is set free and allowed to move toward the earth, the velocity it will acquire in 1 sec. will be 1-980th that acquired at the earth's surface, that is, 1 cm. per sec., and the momentum generated will be 1 (gram-mass) $\times$ 1 (cm. per sec.) = 1 unit of momentum.

106. The Dyne. A name has been given to that force which, when it has acted on a gram-mass for 1 sec., will have given it a velocity of 1 cm. per sec.; it is called a **dyne.**

It will be noticed that there is a distinction in nature between a gram-mass and a gram-force; and when we use the

word *gram*, we must have clearly in mind whether it is a portion of matter or a force.

A gram-mass is the same wherever it be taken—to the north pole, to the moon or to a distant star, it is just so much matter; but a gram-force is not constant all over the earth's surface, as the earth's attraction on a body on its surface is different at different places. At the equator it is slightly smaller than at the poles; but a dyne is constant everywhere in the universe, and hence it is called an *absolute unit* of force.

A Dyne is that force which acting on 1 gram-mass for 1 sec. will generate a velocity of 1 cm. per sec.; or in other words, **a dyne is that force which acting on 1 gram-mass will give it an acceleration of 1 cm. per sec. per sec.**

PROBLEMS

1. A force of 1 dyne acts on a mass of 1 gram. Find the velocity produced in 1 sec., 2 sec., 10 sec. What is the acceleration?

2. If the mass were 10 grams, what would be the velocity produced in 1 sec., 2 sec., 10 sec? What would be the acceleration?

3. If the force were 10 dynes and the mass 1 gram, what would be the velocity in 1 sec., 2 sec., 10 sec., and the acceleration?

4. A force of 2000 dynes acts on a mass of 400 grams. Find the velocity at the end of 1 sec., 2 sec., 10 sec.; also the acceleration, and the momentum at the end of 10 sec.

5. A force of 10 dynes acts on a body for 1 min., and produces a velocity of 120 cm. per sec. Find the mass, and the acceleration.

107. Independence of Forces. It is to be observed that each force produces its own effect, measured by change of momentum, quite independently of any others which may be acting on the body.

Suppose now a person to be at the top of a tower 64 feet high. If he drops a stone, it will fall vertically downward and will reach the ground in 2 seconds. Next, let it be thrown outward in a horizontal direction. Will it reach the ground as quickly?

By the Second Law the force which gives to the stone an *outward* velocity will act quite independently of the force of gravity which gives the *downward* velocity. A horizontal velocity can have no effect on a vertical one, either to increase or to diminish it. Hence the body should reach the ground in 2 seconds, just the same as if simply dropped.

This result can be tested experimentally in the following way:

A and *B* (Fig. 109) are two upright supports through which a rod *R* can slide. *S* is a spring so arranged that when *R* is pulled back and let go it flies to the right. *D* is a metal sphere through which a hole is bored to allow it to slip over the end of *R*. *C* is another sphere, at the same height above the floor as *D*.

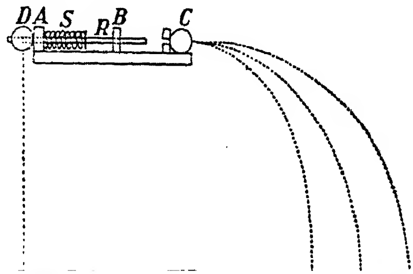


FIG. 109.—The ball *C*, following a curved path reaches the floor at the same time as *D* which falls vertically.

The rod *R* is just so long that when it strikes *C*, the sphere *D* is set free. Thus *C* is projected horizontally outward, while *D* drops directly down.

By pulling *R* back to different distances, different velocities can be given to *C*, and thus different paths described, as shown in the figure.

It will be found that no matter which of the curved paths *C* takes it will reach the floor at the same time as *D*.

PROBLEMS

1. From a window 16 ft. above the ground a ball is thrown in a horizontal direction with a velocity of 50 ft. per second. Where will it strike the ground?

2. A rifle is discharged in a horizontal direction over a lake from the top of a cliff 19·6 m. above the water, and the ball strikes the water 2500 m. from shore. Find the velocity of the bullet outward supposing it to be uniform over the entire range.

3. In problem 2 find the velocity downward at the moment the ball reaches the water; then draw a diagram to represent the horizontal and vertical velocities, and calculate the resultant of the two.

108. Newton's Third Law of Motion. The Third Law relates to actions between bodies.

Let us tie a string to each end of a spring balance and then have two persons, A and B, pull on the strings in opposite directions until the balance indicates (say) 15 pounds. Then it is evident that A pulls B with a force of 15 pounds, and B pulls A with an equal force and in the opposite direction; or, the *action* of A on B is equal and opposite to the *reaction* of B on A. Next, let B tie his string to a post. Then, as before, the post pulls A with the same force that A pulls it, or the action and the reaction are equal and opposite.

If one presses the table with the hand, there is an equal upward pressure exerted by the table on the hand.

A weight is suspended by a cord; the downward pull exerted on the support by the weight is equal to the upward pull exerted by the support to which the cord is fastened.

In all the above cases the action between the two bodies is either a pressure or a tension, *i.e.*, a force trying to push together or one trying to pull apart, and this force produces no motion, since neither body is free to move.

Next, consider what happens when a person jumps from a boat to the shore. The force exerted causes him to go forward and, at the same time, the boat to go backward, and the total effect of the force is the same in the two directions, that is, the momentum of the person forward is equal to the momentum of the boat backward.

On considering the above and numerous other examples, we recognize the truth of Newton's Third Law, which states: **To every action there is always an equal and opposite reaction.**

The following experiment illustrates the third law:

A and B (Fig. 110) are two exactly similar ivory or steel balls, suspended side by side. A is drawn aside to C, and then allowed to fall and strike B. At once A comes to rest, and B moves off with a velocity equal to that which A had.

Here the *action* is seen in the forward momentum of B, the *reaction* in the equal momentum in the opposite direction which just brings A to rest. Of course, if we call the latter the *action*, the former is the *reaction*.

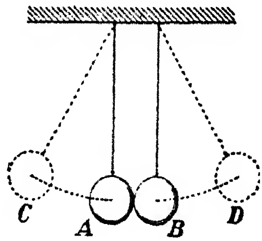


FIG. 110.—The action of A on B is equal to the reaction of B on A.

Suppose now A and B to be sticky putty balls, so that when they collide they stick together; they will both move forward with one-half the velocity which A had on striking. A loses in momentum just w B gains.

PROBLEMS

1. A 200-lb. man dives horizontally forward from the stern of a motor-boat which weighs 1200 lb., with a speed of 6 ft. per sec. With what speed does the boat begin to move in the opposite direction?

2. A hollow iron sphere is filled with gunpowder and exploded. It bursts into two parts; one part, being one-quarter of the whole, flies in one direction with a velocity of 75 m. per sec. What is the velocity of the other part?

3. Suspend an iron ball (Fig. 111) about 3 inches in diameter with ordinary thread. By pulling slowly and steadily on the cord below the ball, the cord above breaks, but a quick jerk will break it below the ball. Apply the first law to explain this.


FIG. 111.—An iron ball suspended by a thread.

4. A rifle weighs 8 lb. and a bullet weighing 1 oz. leaves it with a velocity of 1500 ft. per sec. Find the velocity with which the rifle recoils.

5. An apple falls to the earth. Does the earth move to meet the apple? Can you detect it? Why?

6. Sometimes, in putting a handle in an axe or a hammer, it is accomplished by striking on the end of the handle. Explain how the law of inertia applies here.

7. A man weighing 150 lb. jumps from a row-boat weighing 100 lb. If his velocity forward is 10 ft. per sec., what is the velocity of the boat backward?

8. When you stamp your feet on the pavement, why does the snow come off?

9. A bag of sand of mass 10 lb. hangs from the end of a long cord, and a bullet of mass 1 oz. is fired into it. The bag starts moving with a velocity of 20 ft. per sec. What was the velocity of the bullet on striking the bag?

10. A motor-boat weighing 3000 lb. and a row-boat, weighing with contents 500 lb., float at rest 21 ft. apart. A rope is thrown from one to the other, and by pulling gently and steadily on it they are brought together. What are their relative velocities and how far will each move?

CHAPTER XVIII

MOMENT OF A FORCE; RESULTANT OF FORCES

109. Moment of a Force. If you have to turn a nut which is rusted tight you can exert the greatest turning effort by using a wrench with a long handle. Again if you wish to turn a wheel which is hard to move you do not take hold of the hub, but of the rim (*i.e.*, as far as possible from the axis), and you exert a force at right angles to the spoke where you take hold. Similarly, in stormy weather, in order to keep the ship on her course the wheelsman grasps the wheel by the pins at the rim and exerts a force at right angles to the line joining the axis to the point where he takes hold (Fig. 112). If a machine is driven by a crank, the longer the crank is the greater is the turning effort which can be exerted.

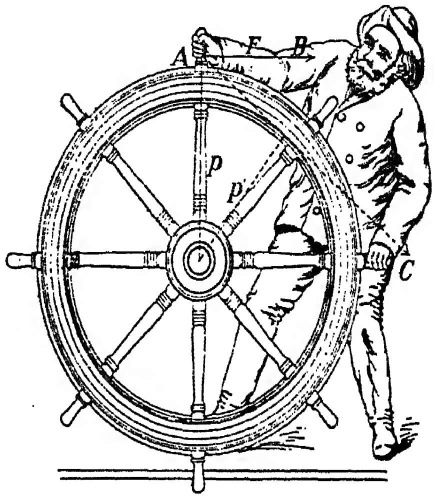


FIG. 112.—The moment of a force depends on the force applied and its distance from the axis of rotation.

From our experience we know that the turning effect upon the wheel is proportional to the force exerted and also to the distance from the axis of the point where the force is applied.

Let F = the force applied,

p = the perpendicular distance from the axis to the line AB of the applied force.

By experience we know that the power to turn the wheel depends directly on F and on p, and is therefore proportional to Fp. This product Fp is called the moment of the force F about the axis. **The moment of a force about a point is the turning effect of the force about the point. It is measured by the product of the force and the perpendicular distance drawn from the point to the line of action of the force.**

If the direction of the force F is not perpendicular to the line joining its point of application to the axis, the moment is clearly not so great, since part of the force is spent uselessly in pressing the wheel against its axis. In Fig. 112 if AC is the new direction of the force, then p', the new perpendicular, is shorter than p, and hence the product Fp' is smaller.

110. Experiment on Moments. The tendency of forces to produce rotation about a point may be studied experimentally by using apparatus shown in Fig. 113. AB is a metre stick provided with a slider F which carries a knife edge by which the stick is supported. The slider is moved until the metre stick just balances in a horizontal position. The masses P and W are then suspended from the stick by loops of thread and adjusted until the stick balances once more.

FIG. 113.—Testing the principle of moments.

Five or six experiments should be made, changing the masses and their distances from F and tabulating the results as follows:

	Arm of P FD	Moment of P $P \times FD$	W	Arm of W FC	Moment of W $W \times FC$
200 gm.	35 cm.	7,000	500 gm.	14 cm.	7,000
300 "	40 "	12,000	400 "	30 "	12,000

It will be found that in every case the moment of P about F equals the moment of W about F.

The experiment may be varied by attaching a third mass Q on the same side of F as P. In this case both P and Q will tend to produce rotation in a clockwise direction, while W will tend to cause contra-clockwise rotation. On taking moments it will be found that the sum of the clockwise moments equals the sum of the contra-clockwise moments.

111. Principle of Moments. In the experiments just described the lines of action of the forces were parallel. Fig. 114 shows how apparatus may be arranged so that the forces are not parallel.

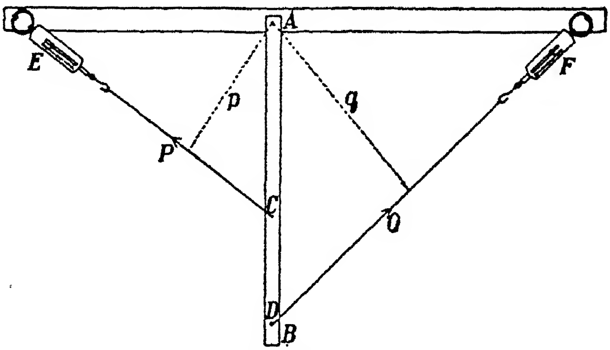


Fig. 114.—Testing the principle of moments.

AB is a wooden strip about 100 cm. long pivoted at A to the top of the blackboard. A chalk mark is made along one edge of the strip when it is hanging freely. Cords fastened to the hooks of the spring-balances E and F are then attached at C and D and adjusted until the strip takes up its original position again. P and Q, the readings of the spring-balances, are then taken and the perpendiculars p and q measured.

The moment of P about A is Pp, tending to make the rod rotate in a clockwise direction; while the moment of Q about A is Qq, tending to produce contra-clockwise rotation. Since the rod is in equilibrium Pp should be found equal to Qq.

Example.—In an experiment

$$P = 700 \text{ gm.}, \; p = 73 \text{ cm.}; \; Pp = 51{,}100,$$
$$Q = 1{,}000 \text{ gm.}, \; q = 51 \text{ cm.}; \; Qq = 51{,}000.$$

These and similar experiments lead us to a conclusion called the ***Principle of Moments:*** **When a body free to turn about a point is in equilibrium, the sum of all the clockwise moments about that point must equal the sum of all the contra-clockwise moments about the point.**

112. Centre of Gravity of a Body. In performing the experiment described in § 110, care was taken to balance the metre stick before attaching the weights. A uniform rod or stick will balance on a pivot or fulcrum placed at its centre. A non-uniform rod, such as a fishing-rod, balances at a point closer to the thicker end. **This point of balance is called the *Centre of Gravity* of a body and the action of gravity on the body produces no turning effect or moment about this point. From the standpoint of moments we can consider the whole weight of the body as being concentrated at the centre of gravity.**

The problem of determining the centres of gravity of various bodies will be considered in a later chapter.

113. Resultant of Parallel Forces in the same Direction. This may be illustrated by the following experiment:

Weigh a metre stick and find C, its centre of gravity. Attach it to spring-balances by loops of thread placed at A and B (Fig. 115). Suspend a weight W from the rod by a thread tied at C.

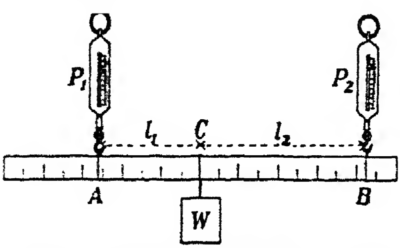


FIG. 115.—Finding the resultant of parallel forces.

See that the rod is horizontal and take the readings P_1, P_2 on the balances; measure also the distances l_1 and l_2 of the weight from P_1 and P_2. Repeat for different positions of A and B.

Since W is suspended from the centre of gravity of the rod, it is evident that we can consider the total weight at C as being $W + w$ where w is the weight of the rod.

Tabulate the results as follows:

P_1	P_2	$P_1 + P_2$	$W + w$	$P_1 \times l_1$	$P_2 \times l_2$
200 gm.	100 gm.	300 gm.	300 gm.	4000	4000
300 "	200 "	500 "	500 "	6000	6000

It will be found that $P_1 + P_2 = W + w$ and that $P_1 \times l_1 = P_2 \times l_2$ in every case. Now $W + w$ balances P_1 and P_2; hence the resultant of P_1 and P_2 must be equal to $W + w$ and must act at C vertically upward, that is, parallel to P_1 and P_2.

Also $P_1 \times l_1$ is the moment of P_1 about C and $P_2 \times l_2$ is the moment of P_2 about C, and these moments have been found equal. We conclude then that **the resultant of two parallel forces acting in the same direction is equal to the sum of the forces and its point of application is so situated that the moments of the two forces about the point are equal.**

114. Equilibrium Conditions for Parallel Forces. From experiments similar to that described in the preceding article we arrive at the following conditions for the equilibrium of a body acted on by a number of parallel forces in one plane:

1. The sum of the forces acting in one direction equals the sum of the forces acting in the opposite direction.

2. The sum of the moments tending to rotate the body clockwise about any point in the plane is equal to the sum of the moments tending to rotate it contra-clockwise about the same point.

PROBLEMS

1. A metre stick just balances at the 50-cm. mark. Masses of 50 and 100 gm. are then attached on opposite sides of the fulcrum and the stick balances once more. If the 50-gm. mass is at the 10-cm. mark, where is the 100-gm. mass?

2. A uniform plank is pivoted at its centre and just balances when two boys weighing 100 and 120 lb. are on opposite sides of the fulcrum. If the heavier boy is 5 ft. from the fulcrum, where is the other?

3. A boy pushes on the pedal of his bicycle with a force of 30 pounds. If the crank, which is 8 in. long, is horizontal and if the push is vertical, what is the moment of the force? Find the moment if the direction of the push makes an angle of 60° with the crank.

4. A rod is 4 ft. long (Fig. 116), and one end rests on a rigid support. At distances 12 in. and 18 in. from that end weights of 20 lb. and 30 lb., respectively, are hung. What force must be exerted at the other end in order to support these two weights? (Neglect the weight of the rod; also in problems 5 and 6.)

Fig. 116.—What force is required to lift the weights?

5. Two men of the same height carry on their shoulders a pole 6 ft. long, and a mass of 121 lb. is slung on it 30 in. from one of the men. How many pounds does each support?

6. A man carries two baskets, one on each end of a stick 30 in. long, and to balance them he grasps it 12 in. from one basket. If the total weight is 25 lb. find the weight of each basket.

7. An angler hooks a fish. Will the fish appear to pull harder if the rod is a long or a short one? Explain, using the principle of moments.

Unlike Parallel Forces.—Couple. Attach a string to each end of a rod lying on a table, and pull on these with equal forces P in parallel directions (Fig. 117). The rod moves forward in the direction of the force.

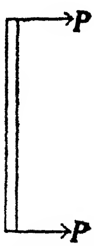


Fig. 117.—Motion of translation only.

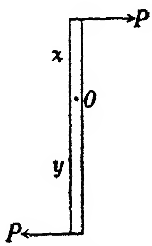


Fig. 118.—Motion of rotation only.

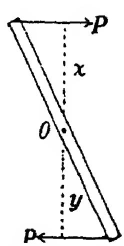


Fig. 119.—Motion of rotation only.

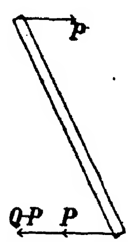


Fig. 120.—Translation and rotation.

Next, pull with equal forces but in opposite senses (Fig. 118). Now the rod simply turns about a vertical axis without moving foward as a whole.

Two equal unlike parallel forces are called a couple.

Let us calculate the moment of this couple about any point O in the rod (Figs. 118 and 119). It is evident that the total turning effect is

$$Px + Py = P\,(x + y) = Pd,$$

where d is the perpendicular distance between the lines of action of the forces. Moreover it is evident that the magnitude of the moment is independent of the position of O.

Next, pull one end of the rod with a force P, and the other with a greater force Q (Fig. 120). This force Q may be considered as made up of two components,

$$P, \text{ and } Q - P.$$

The two forces P, P will form a couple and will produce rotation of the rod, while the force $Q - P$ will produce a motion of the rod as a whole, or a translation, in the direction of the force.

116. Parallelogram of Forces. In § 97 it was shown that if two velocities are given to a body, it will have a resultant

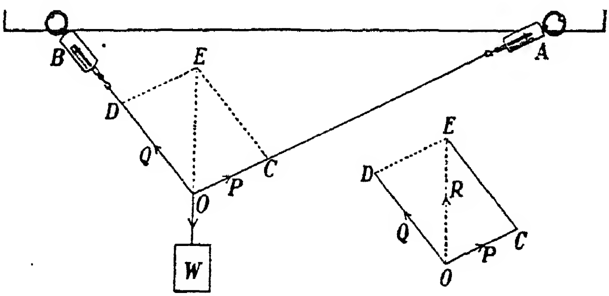


FIG. 121.—How to demonstrate the law of Parallelogram of Forces.

velocity whose magnitude and direction can be determined by the parallelogram law. If two forces which are not parallel act on a body, they are equivalent to a single one which can be determined in the same manner. This can be shown experimentally in the following way:

Suspend two spring-balances A and B from nails or hooks in a horizontal bar (Fig. 121) which may conveniently be the frame above the blackboard. Tie three strings together at O and attach the other ends of two of them to the hooks of the balances. On the third string hang a weight W pounds. This string will take a vertical direction and the tension in it will be W pounds. The tensions in the other strings will be given by the readings on the spring-balances. Let A show P pounds and B show Q pounds. It is plain that the knot at O is kept in equilibrium by the three forces, P acting along OA, Q along OB and W acting vertically downwards.

The force W may be looked upon as balancing the other forces P and Q, and hence if R is the resultant of P and Q (that is, the single force which is equivalent to P and Q acting together), it must be equal in magnitude to W but be acting in the opposite sense, that is, upwards.

Now draw on the blackboard immediately behind the strings (or in some other convenient place), lines parallel to the strings OA, OB, and make OC, OD as many units long as there are pounds shown on A, B, respectively.

Then carefully complete the parallelogram $OCED$ and measure the diagonal OE. It will be found to be in the vertical and to be W units long.

Now we know that the resultant of P and Q acts vertically since it balances the vertical force W. Hence the line OE represents the resultant of P and Q in both direction and magnitude.

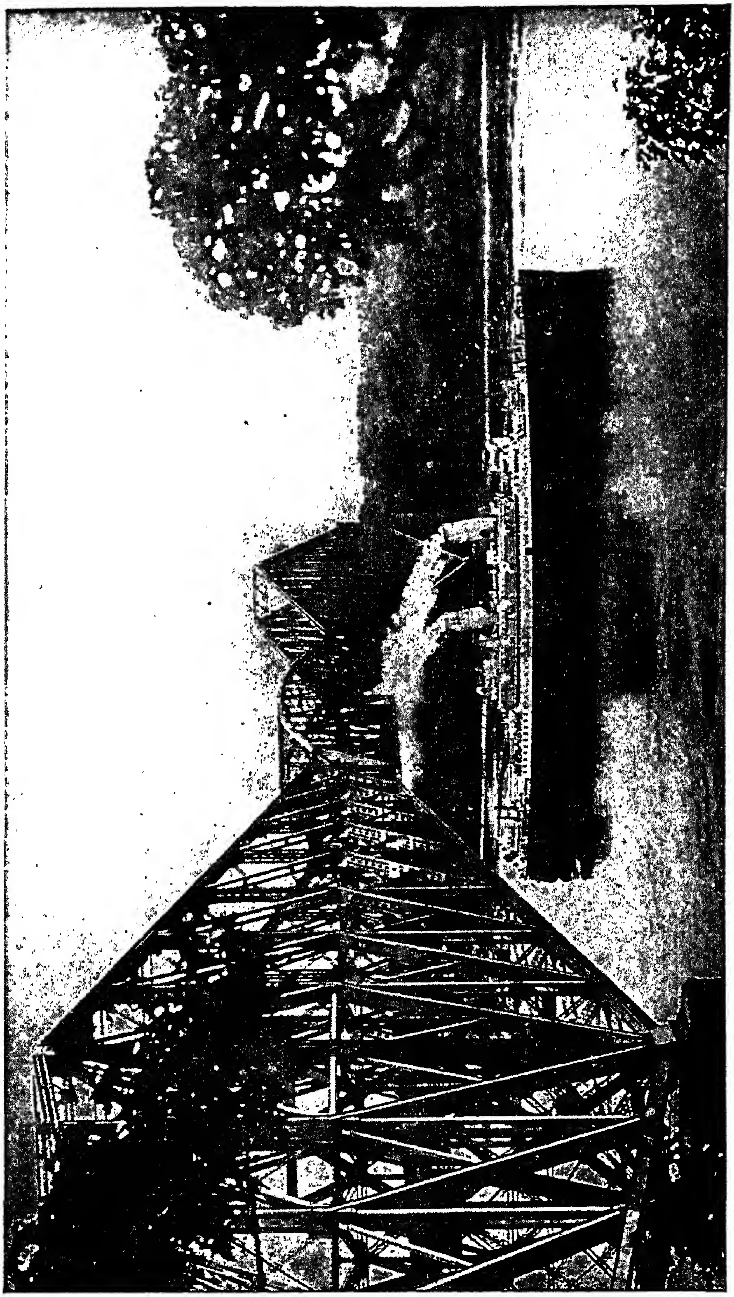
From these experiments we deduce the proposition known as the *Parallelogram of Forces:* **If two forces acting at a point are represented in magnitude and direction by two sides of a parallelogram, then their resultant will be represented, in magnitude and direction, by the diagonal between the two sides.**

PROBLEMS

1. Find the resultant of 15 pounds and 36 pounds, acting at right angles to each other.

2. A weight is supported by two strings which make an angle of 90° with each other. The tension of one string is 9 pounds, that of the other 12 pounds; what is the weight?

3. Two ropes are attached to a stone, and one man exerts a force of 100 pounds, while another exerts a force of 60 pounds at an angle of 30° with the other. Draw a good diagram to scale and from it find the resultant, also the angle between its direction and that of the smaller force.



'HE Q

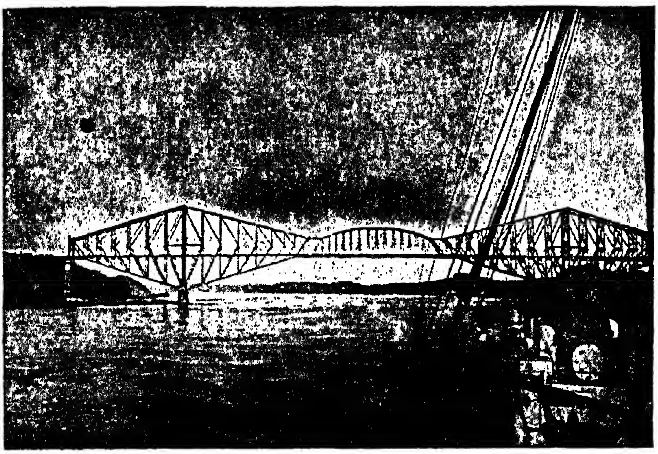
This is the largest cantilever bridge in the world, the span between pier-centres being 1,800 ft. It crosses the St. Lawrence River nine miles west of the city of Quebec. It was completed September 19, 1917, and contains roadways for railway trains, automobiles and pedestrians. The first train crossed it on Oct. 17, 1917, and it was opened for general traffic Dec. 3, 1917. See Encyclopedia Britannica, Article "Bridge."

(Photograph supplied by
Canadian National Railways)

4. The resultant of two forces at right angles to each other is 80 pounds, and one force is $\frac{3}{4}$ as great as the other. Find the magnitude of each.

5. A team of horses is pulling a freight-car and exerts a force of 800 pounds in a direction making an angle of 20° with the track. By means of a figure drawn to scale, find how great a force pulls the car along the track. What does the other part of the force do?

6. A telephone lineman is supported on a small carriage which can run along a cable from pole to pole. When he is midway between two poles which are 100 ft. apart there is a sag of 5 ft. in the cable. If the combined weight of the man and his carriage is 180 pounds, find the tension of the cable.



THE GREAT QUEBEC BRIDGE
Photographed from a steamer passing up the river.

CHAPTER XIX

GRAVITATION

117. Law of Gravitation. One of our earliest observations is that a body, when not supported, falls toward the earth. This action we say is due to *the attraction of the earth.*

Now the earth is one of a family of planets which revolve about the sun, while certain other smaller bodies, called moons, or satellites, revolve about the planets. After many years of observation and study astronomers were able to show that each planet follows a path which has the form of an ellipse, the sun being at one focus; and that the satellites of a planet also revolve in ellipses with the planet in one focus. Certain other simple laws regarding the rate at which the bodies travel in their orbits were also discovered.

This was early in the 17th century, and various scientific people were in the habit of discussing why these motions were so and were wondering just what was the underlying cause. Then Newton examined the question, and he was able to show that, if we suppose the sun to attract the planets, and the planets to attract their satellites, according to a certain simple law, the motions of these bodies would of necessity be precisely what had been observed. The hypothesis was so simple, and it explained the motions so completely that it was at once accepted as true. This hypothesis is known as the Newtonian Law of Gravitation.

Having shown conclusively that the heavenly bodies, with their great masses, attract each other according to his law, Newton was led to the belief that all bodies, no matter what their mass or how they are distributed, attract each other in the same way. This is known as the *Law of Universal Gravitation.*

118. Newtonian Law. Let m, m' be the masses of two particles of matter and r the distance between them. Then Newton's Law of Universal Gravitation states that the attraction between m and m' is proportional directly to the product of their masses, m and m', and inversely to the square of r, the distance between them.

In algebraical language, the force is proportional to mm'

If m, m' are small spheres, each containing 1 gram-mass* and r, the distance between their centres, is 1 cm., then the force = $\frac{1}{15000000}$ dyne (and 1 dyne = $\frac{1}{980}$ gram-force). This is an extremely small quantity, and the attractions between ordinary masses are very small.

For example, a lead sphere 1 metre in diameter contains 5,937,600 grams or nearly 6·6 tons, yet if two such spheres be placed with just 1 cm. between their surfaces, the attraction between them will be only 227 dynes or 0·22 gram-force.

It is to be noted that though the Newtonian Law states *how* two bodies act toward each other it does not state *why*. The *reason why* the attraction takes place is one of the mysteries of nature.

119. Attraction exerted by a Sphere. Some persons in years gone by used to argue that the earth could not be a sphere, since the people on the other side from us would fall off. But if we assume that the earth attracts toward its centre all objects on its surface, then all difficulty disappears. No matter where we are on the sur-

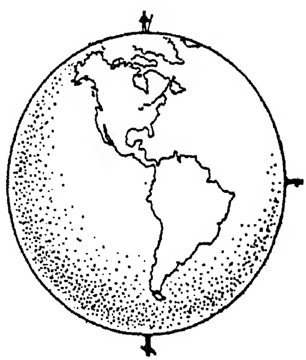


Fig. 122.—A person is attracted to the centre of the earth.

*Lead spheres 5·5 mm. in diameter (the size of a large pea) contain 1 gram-

face of the earth, when we stand upright our feet are toward the earth's centre (Fig. 122).

It can be shown by mathematical calculation that, assuming the truth of Newton's Law of Universal Gravitation, a homogeneous sphere attracts a body outside of it as though all its matter were collected at its centre.

120. Weight of a Body. Consider a mass m at A on the earth's surface (Fig. 123). The attraction of the earth on the mass is the *weight* of the mass (§§ 17, 105). The mass also attracts the earth with an equal force, since action and reaction are equal.

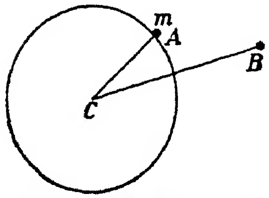


FIG. 123.—Attraction of the earth on a mass on its surface and also twice as far away from the centre.

If m is a pound-mass, the attraction of the earth on it is a *pound-force*; if it is a gram-mass, the attraction is a *gram-force*. We see then that if the whole mass of the earth were condensed into a particle at C and a pound-mass were placed 4000 miles from it, the attraction between the two would be 1 pound-force.

Next, suppose the pound-mass to be placed at B, 8000 miles from C. Then the force is not but $\frac{1}{2^2}$ or $\frac{1}{4}$ of its former value; that is, the *weight* of a pound-mass 4000 miles above the earth's surface would be $\frac{1}{4}$ of a pound-force.

If it were 2000 miles from the earth's surface or 6000 miles from its centre, this distance is $\frac{6000}{4000}$ or $\frac{3}{2}$ of its former distance, and the force of attraction

$$\frac{1}{(\frac{3}{2})^2} \text{ of 1 pound-force.}$$

QUESTIONS AND PROBLEMS

1. If the earth's mass were doubled without any change in its dimensions, what would be the weight of a pound-mass on its surface?

Could one use ordinary balances and the same weights as we use now?

2. How far from the earth's centre must a gram-mass be if the earth's attraction for it is $\frac{1}{850}$ of a gram-force? What is a dyne?

3. Find the weight of a body of mass 100 kilograms at 6000, 8000, 10,000 miles from the earth's centre.

4. The diameter of the planet Mars is 4230 miles, and its density is $\frac{7}{10}$ that of the earth. Find the weight of a pound-mass on the surface of Mars.

5. At either pole of the earth the value of g is actually $\frac{1}{191}$ greater than its value at the equator; but if the earth were at rest, other things remaining unchanged, the former value would be only about $\frac{1}{588}$ greater than the latter. Explain each of these facts.

6. A spring-balance would have to be used to compare the weight of a body on the sun or the moon with that on the earth. Explain why.

7. If two platinum spheres, each having a mass of 11,000 kg., were placed with their centres 1 metre apart, there would be 6·87 mm. between their surfaces. Show that the attraction between the spheres would be only 806$\frac{7}{8}$ dynes, or 0·82 gram-force.

CHAPTER XX

WORK AND ENERGY

121. Definition of Work. When one draws water from a cistern by means of a bucket on the end of a rope; or when bricks are hoisted during the erection of a building; or when land is ploughed; or when a blacksmith files a piece of iron; or when a carpenter planes a board; it is recognized that work is done.

We recognize, too, that the amount of work done depends on two factors:

(1) The magnitude of the force required to lift the bucket or the bricks, or to draw the plough, to push the file, or to drive the plane.

(2) The distance through which the water or bricks are lifted or the plough, file or plane is moved.

In every instance it will be observed that a force acts on a body and causes it to move. In the cases of the water and the bricks the forces exerted are sufficient to lift them, *i.e.*, to overcome the attraction of the earth upon them; in the other cases sufficient force is exerted to cause the plough or the file or the plane to move.

In physics the term *Work* denotes the quantity obtained **when we multiply the force by the distance, measured in the direction of the force, through which it acts.**

In order to do work, force must be exerted on a body, and the body must move in the direction in which the force acts.

122. Units of Work. By choosing various units of force and of length we obtain different units of work.

If we take as the unit of force a pound and as the unit of length a foot, the unit of work will be a foot-pound.

If 2000 pounds mass is raised through 40 feet, the work done is $2000 \times 40 = 80{,}000$ foot-pounds.

In the same way, a kilogram-metre is the work done in raising a kilogram through a metre.

If we take a centimetre as unit of length and a dyne as unit of force, the unit of work is a dyne-centimetre. To this has been given a special name, an erg.

Now 1 gram-force $= g$ dynes; (§§ 105, 106)

Hence 1 gram-centimetre of work $= g$ ergs.

To raise 20 grams through 30 cm. the work required is $20 \times 30 = 600$ gram-centimetres $= 600\ g$ ergs $= 600 \times 980$ or 588,000 ergs.

An erg is a very small quantity and another unit, introduced on account of its convenience in electrical calculations, is often used, namely, a joule, which $= 10{,}000{,}000$, or 10^7, ergs.

123. How to Calculate Work. A bag of flour, 98 pounds, has to be carried from the foot to the top of a cliff, which has a vertical face and is 100 feet high.

There are three paths from the base to the top of the cliff. The first is by way of a vertical ladder fastened to the face of the cliff. The second is a zig-zag path, 300 feet long, and the third is also a zig-zag route, 700 feet long.

Here a person might strap to his back the mass to be carried, and climb vertically up the ladder, or take either of the other two routes. The distances passed through are 100 feet, 300 feet, 700 feet, respectively, but the result is the same in the end—the mass is raised through 100 feet.

The force required to lift the mass is 98 pounds-force, and it acts in the vertical direction. The distance *in this direction* through which the body is moved is 100 feet, and, therefore, the

$$\text{Work} = 98 \times 100 = 9800 \text{ foot-pounds.}$$

Along the zig-zag paths the effort required to move the mass is not so great, but the length of path is greater, and the total work is the same in the end.

PROBLEMS

1. Find the work done in exerting a force of 1000 dynes through a space of 1 metre.

2. A block of stone rests on a horizontal pavement. A spring balance, inserted in a horizontal rope attached to it, shows that to drag the stone requires a force of 90 pounds. If it is dragged through 20 ft. what is the work done?

3. The "weight" of a pile-driver, of 2500 lb. mass, was raised through 20 ft. How much work was required?

4. A coil-spring, naturally 30 cm. long, is compressed until it is 10 cm. long, the average force exerted being 20,000 dynes. Find the work done. Find its value in kilogram-metres (g = 980).

5. To push his cart a banana man must exert a force of 50 pounds. How much work does he do in travelling 2 miles?

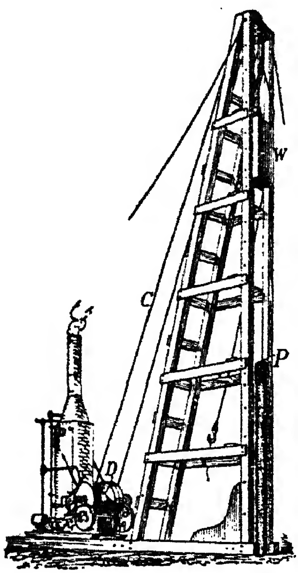


FIG. 124.—A pile-driver. The heavy mass W is raised by the cable C which passes around the drum D, driven by the engine. On falling, W drives the pile P into the ground.

124. Definition of Energy. A log, known as a pile, the lower end of which is pointed, stands upright, and it is desired to push it into the earth. To do so requires a great force, and, therefore, the performance of great work.

The method of doing it is familiar to all. A heavy block of iron is raised to a considerable height and allowed to fall upon the top of the log, which is thus pushed downward. Successive blows drive the pile further and further into the earth until it is down far enough (Fig. 124).

Here work is done in thrusting the pile into its place, and this work is supplied by the pile-driver weight.

It is evident, then, that a heavy body raised to a height is able to do work.

Ability to do work is called *Energy.*

The iron block in its elevated position has energy. As it descends, it gives up this high position and acquires velocity. Just before striking the pile it has a great velocity, and this velocity is used up in pushing the pile into the earth. It is clear, then, that a body in motion possesses energy.

We see thus, that there are two kinds of energy:

(1) Energy of position, or **potential** energy.

(2) Energy of motion, or **kinetic** energy.

125. Transformations of Energy. Energy may appear in different forms, but if closely analysed it will be found that it is always either energy of position, *i.e.*, potential energy, or energy of motion, *i.e.*, kinetic energy.

The various effects due to heat, light, sound, and electricity are manifestations of energy, and one of the greatest achievements of modern science was the demonstration of the Principle of the Conservation of Energy. According to this doctrine, *the sum total of the energy in the universe remains the same.* It may change from one form to another, but none of it is ever destroyed. (See § 5).

A pendulum illustrates well the transformation of energy. At the highest point of its swing the energy is entirely potential, and as it falls it gradually gives up this, until at its lowest position the energy is entirely kinetic.

126. Measure of Kinetic Energy. Suppose a mass m grams to be lifted through a height h cm. (Fig. 125.)

The force required is m grams-force or mg dynes, and hence the work done is mgh ergs.

Suppose now the mass is allowed to fall. Upon reaching the level A it will have fallen through a space h, and it will have a velocity v such that

$$v^2 = 2gh. \qquad (\S\ 92)$$

The potential energy possessed by the body when at B is mgh ergs, and as this energy of position is changed into energy of motion, its kinetic energy on reaching A must also be mgh ergs.

But $$gh = \tfrac{1}{2}v^2$$
and so the kinetic energy $= \frac{1}{2}mv^2$ ergs.

Hence a mass m grams moving with a velocity v cm. per sec. has kinetic energy $\frac{1}{2}mv^2$ ergs.

Now 1 gram-cm. of energy $= g$ ergs, ($g = 980$). Hence
$$\tfrac{1}{2}mv^2 \text{ ergs} = \frac{\frac{1}{2}mv^2}{g} \text{ gram-cm. of energy.}$$
If the mass $= m$ lb. and its velocity $= v$ ft. per sec., its kinetic energy $= \frac{1}{2}mv^2/g$ ft.-pd., where $g = 32$.

127. Matter, Energy, Force. There are two fundamental propositions in science: *Matter cannot be destroyed; energy cannot be destroyed.* The former lies at the basis of analytical chemistry; the latter at the basis of physics. It is to be observed, also, that matter is the vehicle or receptacle of energy. Read §§ 2-5 again.

Force, on the other hand, is of an entirely different nature. On pulling a string a tension is exerted in it, which disappears when we let it go. Energy is bought and sold; force cannot be.

128. Power. Next, let us consider the rate at which energy is supplied. This is called **Power**, which may be defined thus:

***Power* is the rate of doing work.**

A **horse-power** (*h.p.*) is that rate of doing work which would accomplish 33,000 foot-pounds of work per minute, or 550 foot-pounds per second.

In the centimetre-gram-second system the unit of power would naturally be 1 erg per second.

But this is an extremely small quantity, and instead of it we use a **watt**, which is defined thus:

$$1 \text{ watt} = 10{,}000{,}000 \text{ ergs per second,}$$
$$= 1 \text{ joule per second.}$$

It is found that 746 watts = 1 h.p.;

and if 1 *kilowatt* = 1000 watts, then

$$\frac{746}{1000} \text{ kw.} = 1 \text{ h.p. or } \tfrac{3}{4} \text{ kw.} = 1 \text{ h.p. (approx.)}$$

129. The Buying and Selling of Energy. We are accustomed to dealing in flour, sugar, lumber, and other things which we can see and handle, but energy, though invisible and intangible, is quite as real a *thing* and can equally well be bought and sold. Energy is *ability to do work*, and it is as reasonable that we should pay for any energy which is supplied to us as for the objects produced thereby.

Further, it is clear that the charge for energy should depend upon

(i) the rate at which it is supplied;

and (ii) the length of time it is supplied.

For example a house-holder pays for the electrical energy which he uses at a certain rate per *kilowatt-hour* while a municipality buys its electrical energy at so much per *horse-power year*. *One kilowatt-hour is the energy expended when 1 kilowatt power is used for 1 hour.*

PROBLEMS

1. Why does the engineer of a heavy train, with a steep grade before him, try to reach the foot of the grade with a high speed?

2. If a banana man exerts a force of 50 pd. in pushing his cart and travels 2 mi. in 1 hr., at what rate does he work?

3. A man weighing 150 lb. runs up 25 steps, each 7 in. high, in 5 sec. At what rate does he work?

4. A horse draws a carriage along a level road at constant speed. What kind of energy does the carriage possess? If the horse draws the carriage up a hill, what kind of energy does it possess at the top?

5. A steam engine is rated at 120 h.p. and drives a dynamo. If 90% of the engine's power is transformed into electric energy, find the power of the dynamo i

6. A man weighing 150 lb. puts a 90-lb. bag of potatoes on his back and climbs a ladder to a height of 30 ft. in 20 sec. What is the total amount of work he does and the rate at which he does it?

7. What is the h.p. of an engine which raises 400 gal. of water per min. from a depth of 165 ft. (1 gal. = 10 lb.)

8. A rifle bullet weighs 15 gm. and leaves the gun at a speed of 700 metres per sec. Find its energy.

9. A rifle bullet with a speed of 1000 ft. per sec. can penetrate 2 ft. of wood. Through how much wood should it go if its speed were 2000 ft. per sec.?

10. Find the h.p. of an engine which can raise 15 tons of coal (2000 lb. each) in 1 hr. from a pit 500 feet deep.

11. Express 1 kilowatt-hour in joules.

12. How much would it cost to operate a 500-watt electric iron for 4 hours at 2 cents per kwh.

CHAPTER XXI

CENTRE OF GRAVITY

130. A Unique Central Point in Every Body. The meaning of centre of gravity has already been briefly explained (§ 112); we shall now discuss it more fully.

When one side of a carriage is somewhat lower than the other we experience an uncomfortable sensation, as we know that there is a definite position beyond which we must not go or the carriage will upset.

Again, push a book or a piece of board slowly over the edge of a table. It rests safely on the table until it reaches a certain definite position, when it is seen to totter, and if pushed any farther it falls. When in the tottering position draw a line on the underside along the edge of the table. Now turn the object about and push it over the edge again, drawing another line when it is in its critical position. Repeat this several times and then look at the lines drawn. They all meet very approximately in a point, and thus it is seen that as soon as that particular point gets beyond the line of support the body falls over into a new position.

Our everyday experience leads us to believe that there is a unique central point in a body, and if that point goes beyond a certain position the body moves over into a new position of rest.

131. Experiments with a Thin Flat Body. Support an irregular-shaped sheet of metal, or a piece of cardboard, at *A* (Fig. 126*a*), by hanging it on a pin or in some other convenient way. Have a cord attached to the pin, with a small weight on the end of it. Chalk the cord and snap it on the plate, thus

making a straight white line across it. Next, support the body at B (Fig. 126b), and obtain another chalk line. Let it cut the first line at G. Support the plate at other places and get other lines on it. All the lines cut at a single point—the point G—which must be a unique point in the plate.

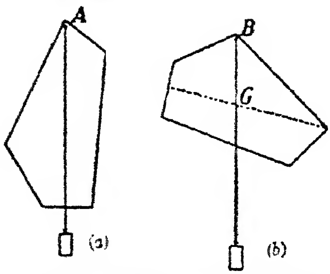


FIG. 126.—How to find the centre of gravity of a flat body.

Now try to balance the plate on the end of a finger. You find the plate balances if it is supported at G. But it is simply the weight of the plate that the finger has to overcome, and we conclude, then, that **the entire weight of the body may be considered as concentrated at a point.** This point is called the ***Centre of Gravity*** of the body. The abbreviation C.G. will be used for Centre of Gravity.

132. Composition of Forces due to Gravity. A body consists of a very great number of particles, and according to the principle of Universal Gravitation the earth attracts every particle with a force which we call its weight. The lines of action of these forces are directed to the centre of the earth, but since that point is 4000 miles away the directions of the forces may be taken to be parallel.

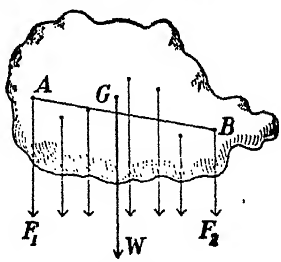


FIG. 127.—The weight of a body acts as its centre of gravity.

These forces will have a single resultant acting at a definite point fixed in the body as can be seen in the following way:

The two forces F_1, F_2, acting on particles at A, B (Fig. 127), will have a resultant, $F_1 + F_2$, acting at a point in AB so situated that the moment of F_1 about the point equals the

moment of F_2 about the point. Further, if the body moves into another position the magnitude and point of action of this resultant will be unchanged.

Next, combine this resultant with a third force F_3, and obtain the point of action of $F_1 + F_2 + F_3$, the resultant of the three forces.

Then combine this resultant with a fourth force; and continuing in this way we at last reach a single resultant of all the forces acting at a definite point in the body.

The sum of all these separate forces is the weight of the body and the point of application of the resultant force is the centre of gravity of the body.

133. To Find the Centre of Gravity of a Body of any Form. Suspend the body by a cord attached to any point A (Fig. 128) in it. Then there are two forces acting on the body, namely, the weight acting downwards at G and the tension of the string acting upwards at A. These are equal in magnitude and form a couple. They cause the body to rotate until G is directly beneath A, in which case the line of action of the weight coincides with the direction of the string, and the tension of the string will just balance the weight of the body. The body will then be in equilibrium.

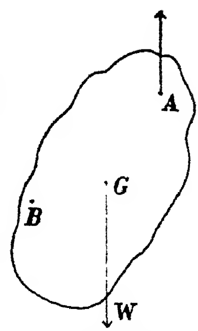


FIG. 128.—How to find the centre of gravity of a body of any form.

Thus, if the body is suspended at A and allowed to come to rest the direction of the supporting string will pass through the centre of gravity.

Next attach a cord at B and hang up the body as before. The direction of the cord will again pass through the C.G.; that point, therefore, will be where the two lines intersect.

134. Centre of Gravity of some Bodies of Simple Form. The centre of gravity of some bodies of simple form can often be deduced from geometrical considerations.

(1) For a straight uniform bar AB (Fig. 129), the centre of gravity is midway between the ends.

. 129.—Centre of gravity of a uniform rod.

(2) For a parallelogram, it is at the intersection of the diagonals; and for a triangle, where the three median lines intersect. (Fig. 130).

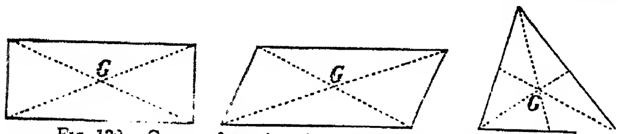


FIG. 130.—Centre of gravity of a parallelogram and a triangle.

(3) For a cube or a sphere, it is at the centre of figure.

135. Condition for Equilibrium. For a body to rest in equilibrium on a plane, the line of action of the weight must fall within the supporting base, which is the space within a cord drawn about the points of support. (See Fig. 131.)

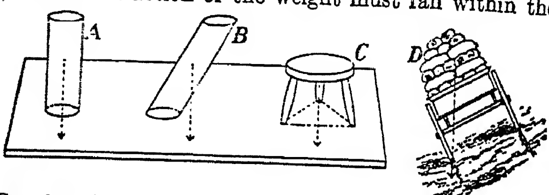


FIG. 131.—A and C are in stable equilibrium; B is not, it will topple over; D is in the critical position.

The famous Leaning Tower of Pisa (Fig. 132) is an interesting case of stability of equilibrium. It is circular in plan, 51 feet in diameter, and 172 feet high, and has eight stages, including the belfry. Its construction was begun in 1174. It was founded on wooden piles driven in boggy ground, and when it had been carried up 35 feet, it began to settle to one side. The tower overhangs the base upwards of 13 feet, but the centre of gravity is so low down that a vertical through it falls within the base, and hence the equilibrium is stable.

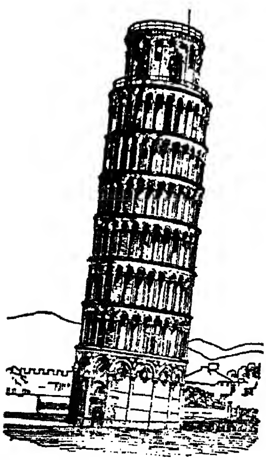


FIG. 132.—The Leaning Tower of Pisa. It overhangs its base more than 13 feet, but it is stable. (Drawn from a photograph.)

136. The three States of Equilibrium. The centre of gravity of a body will always descend to as low a position as possible.

Consider a body in equilibrium, such as the cone *A* (Fig. 133), and suppose that by a slight motion this equilibrium is disturbed. Then, since the body tends to return to its former position, its equilibrium is said to be **stable.** In this case the slight motion raises the centre of gravity, and on letting it go the body tends to return to its original position.

If, however, a slight disturbance lowers the centre of gravity, as in *B* (Fig. 133), the body will not return to its original position, but will take up a new position in which the centre of gravity is lower than before. In this case the equilibrium is said to be **unstable.**

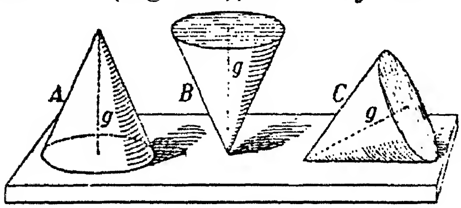


FIG. 133.—Stable, unstable and neutral equilibrium illustrated by a cone.

Sometimes a body, such as a cone resting on its curved surface, (*C*, Fig. 133), rests equally well in any position in which it may be placed. In this case the equilibrium is said to be **neutral.**

An egg standing on end is in unstable equilibrium; if resting on its side, the equilibrium is stable as regards motion in an oval section and neutral as regards motion in a circular section (Fig. 134). A uniform sphere rests anywhere it is placed on a level surface; its equilibrium is neutral.

A round pencil lying on its side is in neutral equilibrium; balanced on its end, it is unstable. A cube, or a brick, lying on a face, is stable.

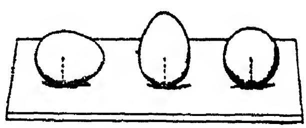


FIG. 134.—An egg in stable, unstable and neutral equilibrium.

The degree of stability possessed by a body resting on a horizontal plane varies in different cases. It increases with the distance through which the centre of gravity has to be raised in order to make the body tip over. Thus, a brick

lying on its largest face is more stable than when lying on its smallest.

QUESTIONS AND PROBLEMS

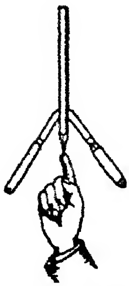


Fig. 135.—Why is the pencil in equilibrium?

1. Why is ballast used in a vessel? Where should it be put?

2. Why should a passenger in a canoe sit on the bottom? Why not stand up?

3. Why is a load of hay easier to upset than a load of grain?

4. Why is a pyramid a very stable structure?

5. Running shoes with rubber soles when thrown up into the air usually land right side up. Why?

6. The low-hung automobiles of the present day are much less easily upset than the cars of twenty years ago. Explain why.

7. A bowl when right-side-up is not easily balanced on the end of a finger, but if up-side-down it is. Why?

8. A pencil will not stand on its point, but if two pen-knives are fastened to it (Fig. 135) it rests on one's finger. Explain why.

9. A wooden toy as illustrated (Fig. 136) will not stand upright unless a mass, such as a potato, is attached on a wire as shown. Explain why.

10. A uniform rod 24 in. long and weighing 5 lb. has a 1-lb. weight on one end. Find the centre of gravity of the whole.

11. A uniform iron bar weighs 4 lb. per ft. of its length. A weight of 5 lb. is hung from one end, and the rod balances about a point 2 ft. from that end. Find the length of the bar.

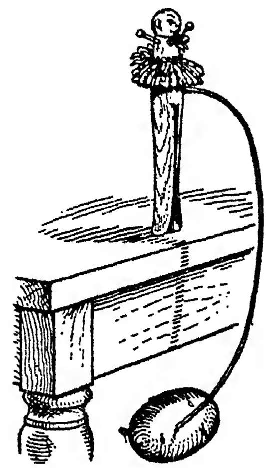
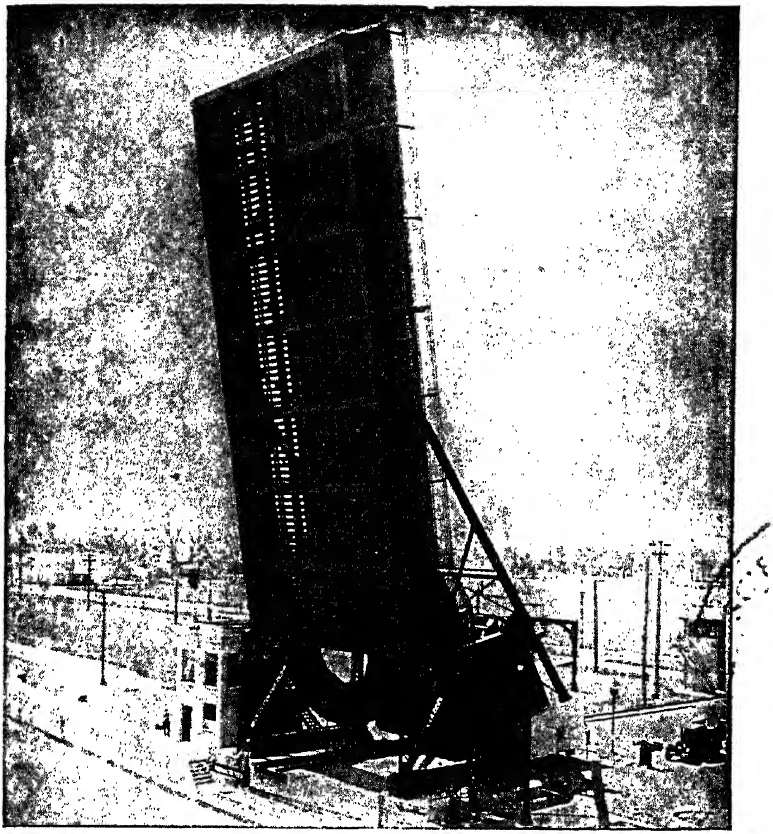
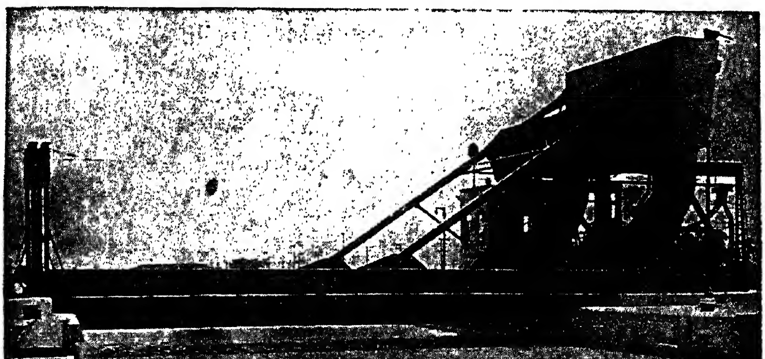


Fig. 136.

12. By means of a uniform rod balanced on his shoulder a man carries a pail of water weighing 12 kg. on one end and a pail of milk weighing 8 kg. on the other. The rod is 1 metre long. If its weight be negligible, at what point should it rest on the shoulder? If it weighs 1 kg., where would it be supported?





BASCULE BRIDGE OVER THE WELLAND SHIP CANAL AT PORT WELLER

● Plate 9

Plate 9

The lower picture shows the moving leaf of the bridge down for the passage of traffic over it; the upper one shows the leaf raised to allow ships to use the canal. Note that the leaf is balanced by a counterweight, the axis around which the bridge turns being through the centre of gravity. As the leaf goes up it also moves back from the canal.

(Photograph supplied by C. W. West,
Superintending Engineer, Welland Canals)

CHAPTER XXII

FRICTION

137. Friction Stops Motion. A stone thrown along the ice will, if "left to itself," come to rest. A railway-train on a level track, or an ocean steamboat will, if the steam is shut off, in time come to rest. The stone, the train and the ship give up their energy of motion but do not receive any energy of position in place of what they have lost. In the same way all the machinery of a factory when the "power" is turned off soon comes to rest.

In all these cases the energy simply seems to disappear and be wasted. As we shall see later, it is transformed into energy of another form, namely, heat; but it is done in such a way that we cannot utilize the heat energy which has been produced.

The stopping of the motion in every instance given is due to friction. When one body slides or rolls over another, there is always friction, which acts as a force in opposition to the motion. Thus there is continually great loss of energy through friction and we try to reduce it to a minimum by the use of oil and grease, but it should be remembered that we should be in serious difficulties if there was no such thing as friction.

If there were no friction between the rails of the railroad and the wheels of the locomotive, or between the tires of the automobile and the pavement of the highway, the locomotive or the automobile could not set itself in motion or accelerate its motion. Friction is not entirely an evil or a nuisance.

138. Every Surface is Rough. The smoothest surface, when examined with a powerful microscope, is seen to have numerous little projections and cavities on it (Fig. 137). Hence, when two surfaces are pressed together, there is a kind of interlocking of these irregularities which resists the motion of one over the other.

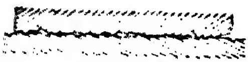


FIG. 137.—Roughness of a surface as seen under a microscope.

139. Laws of Sliding Friction. Friction depends upon the nature of the substances and the roughness of the surfaces in contact. By means of the apparatus shown in Fig. 138, the laws of sliding friction can be investigated.

A flat block *M* rests on a board, which should be made as nearly horizontal as possible, and a cord attached to *M* passes over a pulley and bears a pan on the end of it. The block can be loaded to any desired amount and weights can be put on the pan.

FIG. 138.—Experiment to find the coefficient of friction.

Let the horizontal board and the block *M* be both of dry pine. Clean the surfaces by rubbing with fine sand-paper and then wipe the dust off carefully. Also rub the block back and forth upon the board. These operations are to give the surfaces a clean and permanent condition.

Weigh *M* and also the pan. Put a weight W on M and a smaller one on the pan, and let the weight of the pan and the mass on it be P. Then the block is pulled by a force P and (supposing there is no motion) sufficient friction between M and the board is called into action to balance P.

Continue adding weights to the pan, doing it carefully and avoiding jerks, until at last the block begins to move. Record the weight of the pan and its contents. This gives us the limiting value of friction for this particular experiment. Repeat the experiment several times, and take the average of the several weights of the pan and its contents.

Let this average $= F$; also let $w =$ weight of the block M, and $W =$ the weight upon it.

Then find the value of $\frac{F}{W +}$.

Next make $W + w$ double what it was before and find the new limiting value of friction. It will be double the former value.

We find that the ratio $\frac{}{W + w}$ is constant; it is called the **static coefficient of friction** between the block M and the surface.

The friction does not depend upon the area of the surfaces in contact; and it is greater at the instant of starting than during motion.

For dry pine, smooth surfaces, the coefficient is about 0·25 *i.e.*, a 40-pound block would require a 10-pound force to drag it over a horizontal pine surface.

For iron on iron, smooth but not oiled, the coefficient is about 0·2; if oiled, about 0·07. This shows the use of oil as a lubricant.

140. Rolling Friction. When a wheel or a sphere rolls on a plane surface, the resistance to the motion produced at the point of contact is said to be due to *rolling* friction. This, however, is very different from the friction just discussed, as there is no sliding. It is also very much smaller in magnitude.

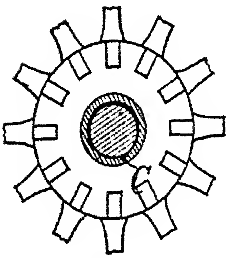


FIG. 139.—Section through a carriage hub, showing an ordinary bearing.

In ordinary wheels, however, sliding friction is not avoided. In the case of the hub of a wagon (Fig. 139) there is sliding friction at the point C.

In ball-bearings (Fig. 140), which are much used in bicycles, automobiles and other high-class bearings, the sliding friction is almost completely replaced by rolling friction, and hence this kind of bearing has great advantages over the other.

QUESTIONS AND PROBLEMS

1. Explain the utility of friction in: (*a*) Locomotive wheels on a railway track. (*b*) Leather belts for transmitting power. (*c*) Brakes to stop a moving car.

2. Why is sand put on the track in starting or stopping a street car or a railway train? Why are chains put on automobiles?

3. The current of a river is less rapid near its banks than in mid-stream. Can you explain this?

4. What horizontal force is required to drag a trunk weighing 150 lb. across a floor, if the coefficient of friction between trunk and floor is 0·3?

5. A brick, 2 × 4 × 8 inches in size, is slid over ice. Will the distance it moves depend on what face it rests upon?

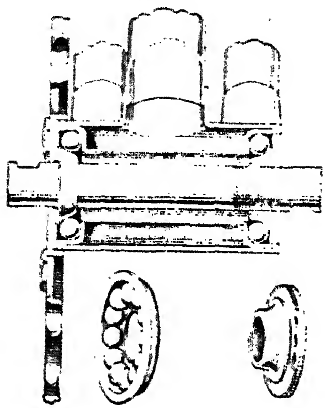


FIG. 140.—Section of the crank of a bicycle. The cup which holds the balls and the cone on which they run are shown separately below. Here the balls touch the cup in two points and the cone in one; it is a "three-point" bearing.

6. A horse pulls a stone-boat weighing 50 lb. with a barrel of water weighing 200 lb. on it for a distance of half a mile. If the coefficient of friction is 0·6, find the work done.

7. When a force of 5 pounds is applied horizontally to a body weighing 75 lb. on a horizontal surface, it just moves. Find the coefficient of friction.

8. A stone weighing 400 grams is thrown along the ice with a velocity of 5 metres per sec., and it comes to rest after sliding 60 metres.

(*a*) What is the initial kinetic energy, in gram-cm.? ($g = 980$)

(*b*) If F grams-force is the friction, what is the amount of work done in bringing it to rest?

(*c*) Putting (*a*) equal to (*b*), find F.

(*d*) From F and the weight of the stone find the coefficient of friction.

9. A motor car weighing 3200 lb. and travelling at the rate of 45 mi. per hr. is brought to rest in a distance of 150 ft. by the application of the brakes.

(*a*) Calculate the average retarding force. ($g = 32$).

(*b*) If the coefficient of friction between the tires and the pavement is 0·65, calculate the maximum force which could be exerted by the brakes without causing the car to skid. How far would the car travel if the maximum force was applied?

(*c*) Suppose the above car when travelling at 45 mi. per hr. strikes a heavy object and is stopped in a distance of 6 ft., estimate the retarding force.

CHAPTER XXIII

MACHINES: LEVERS

141. Importance and Object of Machines. The invention of the practicable steam engine by James Watt about 1770, and soon afterwards the invention of machines for spinning and weaving cotton and other textiles were among the chief causes of the industrial revolution in Britain during the first half of last century. It changed completely the way of living of the people and led to Britain's commercial supremacy throughout the world. This industrialism spread to other countries, especially to the United States which is well-known for the inventiveness of its people. In our own times the mass production of automobiles, electric lamps and other things in common use has been possible only through the use of machines.

A machine is a device by which energy is transferred from one place to another, or is transformed from one kind to another.

The six simple machines, usually known as the *mechanical powers*, are, the lever, the pulley, the wheel and axle, the inclined plane, the wedge, and the screw. All other machines, no matter how complicated, are but combinations of these.

Since energy cannot be created or destroyed, but simply changed from one form to another, it is evident that, neglecting friction, the amount of work put into a machine is equal to the amount which it will deliver.

142. The Lever; First Class. The lever is a rigid rod movable about a fixed axis called the fulcrum. Levers are of three classes.

In Fig. 141 is shown a lever of the first class. By applying a force P at A a force sufficiently great to balance the force W is obtained at B, the lever turning about the fulcrum F.

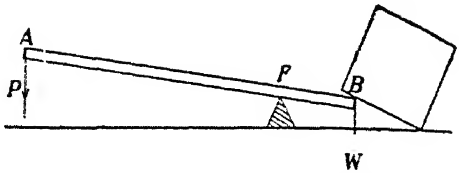


FIG. 141.—A lever of the first class. The fulcrum F is between the applied force P and the weight lifted W.

The relation between the forces P and W follows from the principle of moments, and it can be determined experimentally as follows:

Lay a metre rod on a prism with the 50 cm. mark exactly over the edge of the prism (Fig. 142). If it does not balance add bits of lead or plasticine to the lighter end until it does. Put blocks under the ends to reduce the vibrations.

Suspend a mass W from some graduation, noting its distance from F. This distance BF is one arm of the lever, and the product $W \times BF$ is the moment of W about F.

B

FIG. 142.—Investigating th · of the lever of the

Move the mass P until it just balances W and note the length of the arm AF. The moment of $P = P \times AF$. Make 5 or 6 readings, changing masses and distances each time. Then compare the values of $W \times BF$ and $P \times AF$ for each set of readings. They will be found to be equal.

Applying this result to either figure we see that

$$\text{Force obtained} \times \text{its arm} = \text{Force applied} \times \text{its arm},$$

or
$$\frac{\text{Force obtained}}{\text{Force applied}} = \text{inverse ratio of length of arms.}$$

This is called the **Law of the Lever**, and the ratio W/P is called the **Mechanical Advantage**.

Suppose, for instance, $AF = 36$ inches, $BF = 4$ inches.

Then $W/P = AF/BF$ $36/4 = 9$, the mechanical advantage.

It is evident that the mechanical advantage of a lever of the first class may be greater than, equal to, or less than 1 according to the position of the fulcrum.

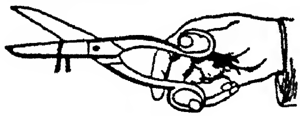


FIG. 143.—Shears, lever of the first class.

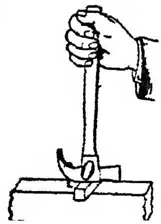


FIG. 144.—Claw-hammer, used as a lever of the first class.

There are many examples of levers of the first class. g tnem are tne common balance, a pump handle, a pair of scissors (Fig. 143), a claw-hammer (Fig. 144).

143. The Lever; Second Class. In levers of the second class the weight to be lifted, or the resistance to be overcome, is placed between the point where the force is applied and the fulcrum.

A lever of this class is shown in Fig. 145. The force P is applied at A, and the force obtained, or the resistance overcome, is at B, between A and the fulcrum F.

The law in this case can be determined experimentally as follows:

Find the position of the centre of gravity F of a metre stick by balancing it on the adjustable knife-edge shown at F in Fig. 146. Support it at this point.

B

FIG. 145.—A lever of the second

FIG. 146.—Demonstrating the law for a lever of the second class.

Now attach a weight W to the rod, noting its distance from the fulcrum F and observe the reading P of the spring-balance when the stick is horizontal. Make 5 or 6 readings, varying the value of W and the point where it is placed.

Compare the products $P \times AF$ and $W \times BF$: they will be found equal; and we have, as in the first class,

Mechanical Advantage $W/P = AF/BF$, a ratio which is greater than 1.

Examples of levers of the second class: nut crackers (Fig. 147), trimming board (Fig. 148), safety valve (Fig. 149), wheel-barrow, oar of a row-boat.

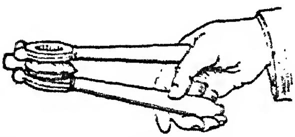


FIG. 147.—Nut-crackers, lever of the second class.

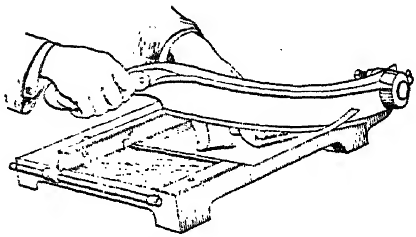


FIG. 148.—Trimming board for cutting paper or cardboard; a lever of the second class.

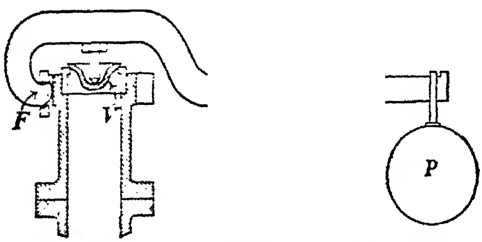


FIG. 149.— A safety-valve of a steam boiler. (Lever of the second class). L is the lever arm, V the valve against which the force of the steam acts, P the applied force which keeps the steam from escaping, F the fulcrum.

144. The Lever; Third Class. In this case the force P is applied between the fulcrum and the weight to be lifted. (Fig. 150).

To investigate this arrangement experimentally the apparatus shown in Fig. 151 may be used.

FIG. 150.—A lever of the third

A wire loop is placed around the metre stick at its centre of gravity and is fastened to the table as indicated.

As before, compare the products $P \times AF$ and $W \times BF$ for various values and positions of W.

These will be found to be equal, and

$$W/P = AF/BF, \text{ the law of the lever.}$$

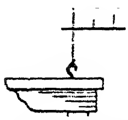


Fig. 151.—Demonstrating the law of the lever of the third class.

Notice that the weight lifted is always less than the force applied, or the mechanical advantage is less than 1.

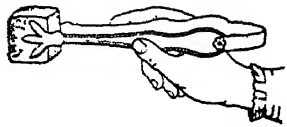


Fig. 152.—Sugar-tongs, lever of the third class.

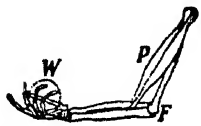


Fig. 153.—Human forearm, lever of the third class. One end of the biceps muscle is attached at the shoulder, the other is attached to the radial bone near the elbow, and exerts a force to raise the weight in the hand.

Examples of levers of this class: sugar-tongs (Fig. 152), the human forearm (Fig. 153); treadle of a lathe or a sewing machine.

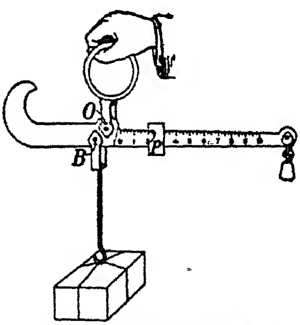


Fig. 154.—The steelyards.

PROBLEMS

1. Explain the action of the steelyards (Fig. 154). To which class of lever does it belong? If the distance from B to O is $1\frac{1}{2}$ in., and the sliding weight P when at a distance 6 in. from O balances a mass of 5 lb. on the hook, what must be the weight of P?

If the mass on the hook is too great to be balanced by P, what additional attachment would be required in order to weigh it?

2. A hand-barrow (Fig. 155), with the mass loaded on it, weighs 210 lb. The centre of gravity of the barrow and load is 4 ft. from the front handles and 3 ft. from the back ones. Find the amount each man carries.

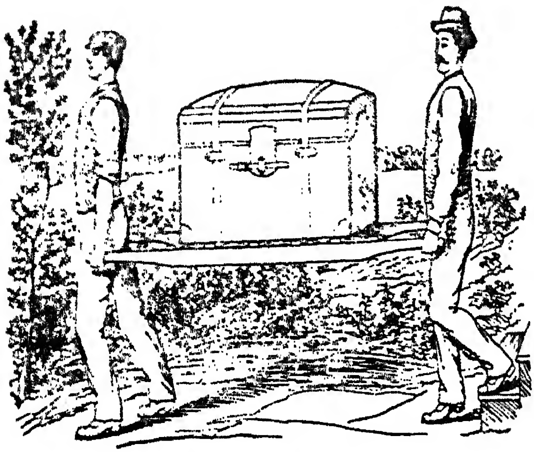


FIG. 155.—The hand-barrow.

3. To draw a nail from a piece of wood requires a pull of 200 pounds. A claw-hammer is used, the nail being $1\frac{1}{2}$ in. from the fulcrum O (Fig. 144) and the hand being 8 in. from O. Find what force the hand must exert to draw the nail.

4. A cubical block of granite, whose edge is 3 ft. in length and which weighs 4500 lb., is raised by thrusting one end of a crow-bar 40 in. long under it to the distance of 4 in. and then lifting on the other end. What force must be exerted?

5. A wheel-barrow with its load (Fig. 156), weighs 120 lb.; the horizontal distances of the handles and of the C.G. of the loaded barrow from the centre of the wheel are 4 ft. and 18 in., respectively. Find the force which must be applied to each handle to lift the legs of the barrow off the ground.

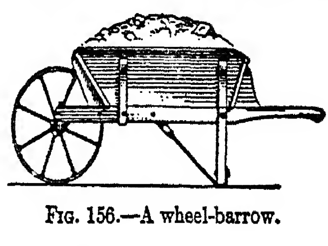
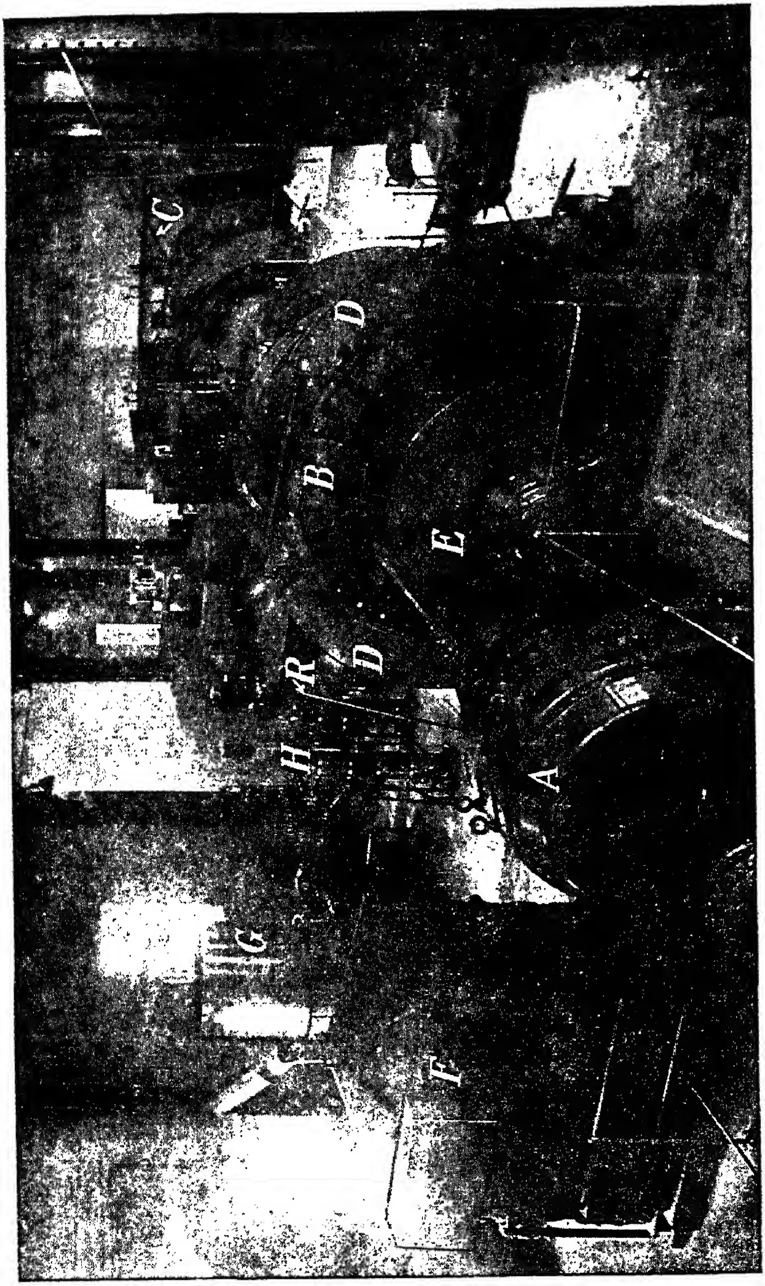


FIG. 156.—A wheel-barrow.

6. In the safety valve (Fig. 149) the distance from the fulcrum to the valve is 4 in. and from the fulcrum to the weight 18 in. If the weight P is 20 lb., what force must the steam exert to be just on the point of escaping?

7. To which class of lever does a shovel belong?


C
D
B
E
D
R
H
A
G
F

These hoists raise the ore to the surface from the level 3,050 ft. below the surface. Development ore is hoisted from as far as 5,000 ft. below the surface and dumped on the 2,600-ft. level to feed the crusher on the 2,900-ft. level from which it falls to the 3,050-ft. level and is then brought to the surface. The two hoists work in the same shaft, each hoist operating two "skips" or baskets, one on each end of a long cable—when one comes up the other goes down. Each skip can carry 6 tons and the hoist handles 210 tons of ore an hour.

The motor *A* is rated at 2,000 h.p. but for short periods it delivers about 3,000 h.p. In *E* are reduction gears. *B* is a drum on which the hoisting cable *C* winds. *D* is one of two brakes. If both brakes are released the drum is free to turn. The brakes are applied by gravity, there being on the end of the rod *R* a concrete block several tons in weight. This can be raised by the brake engine *H* (a kind of hydraulic screw-jack) actuated by oil under high pressure in *G*. In *F* is a liquid rheostat to control the current supply for the motor.

(Photograph supplied by Hollinger Mines)

CHAPTER XXIV

PULLEYS

145. The Pulley. The pulley is used sometimes to change the direction in which a force acts, sometimes to gain mechanical advantage, and sometimes for both purposes.

The pulleys used in experiments should be of very light construction and with well-made bearings, in which there is little friction.

A single fixed pulley, such as is shown in Fig. 157, can change the direction of a force but cannot give a mechanical advantage greater than 1. P, the force applied, is equal to the weight lifted, W.

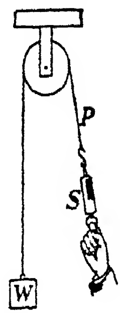


FIG. 157.—A fixed pulley simply changes the direction of force.

By this arrangement a lift is changed into a pull in any convenient direction. It is often used in raising materials during the construction of a building.

By inserting a spring-balance, S, in the rope, between the hand and the pulley, one can show that the force P is equal to the weight W.

In order to apply the principle of energy, suppose the hand to move through a distance a, then the weight rises through the same distance.

Then the work done by the hand $= P \times a$;
The work done in lifting the weight $= W \times a$.
These are equal, hence $P \times a = W \times a$,
or $P = W$,

as tested by the spring-balance.

If the friction is not negligible, pull on the balance until W rises slowly and uniformly. Then the difference between the

weight W and the reading on the balance will give the magnitude of the friction.

An example of the use of a single fixed pulley is seen in Fig. 158, which shows a log being dragged to a river at the right. Six men are required to handle it.

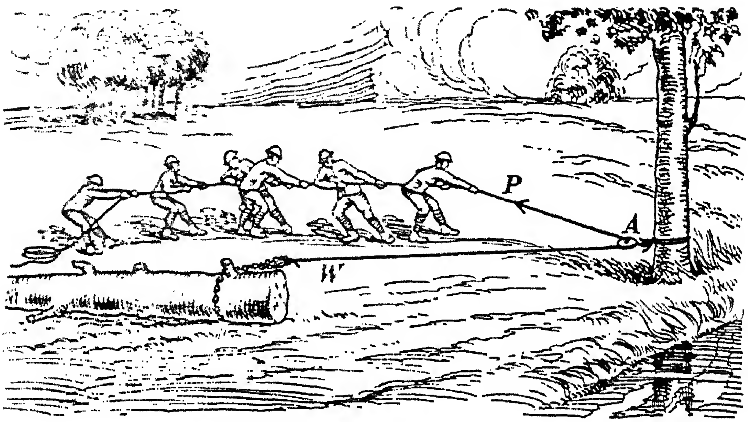


Fig. 158.—Illustrating the use of a single fixed pulley. It is known as "single whip".

146. A Single Movable Pulley. Here the weight W (Fig. 159) is supported by the two portions B and C, of the rope, and hence each portion supports half of it.

Thus the force P, which is indicated by the balance S, is equal to $\frac{1}{2}W$, and the mechanical advantage is 2.

This result can also be deduced from the principle of energy.

Let a be the distance through which W rises. Then each portion, B and C, of the rope, will be shortened a distance a, and so P will be applied through a distance $2a$.

Then, since $P \times 2a = W \times a$,

$W/P = 2$, the mechanical advantage.

For convenience a fixed pulley is generally used in addition as in Figs. 160 or 161.

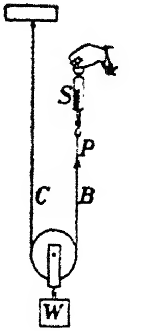


FIG. 159.—With a movable pulley the force exerted is only half as great as the weight lifted.

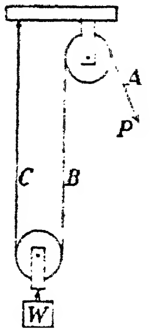


FIG. 160.—With a fixed and a movable pulley the force is changed in direction and reduced one-half.

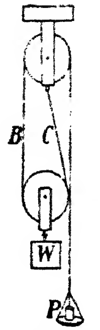


FIG. 161.—One fixed and one movable pulley for greater convenience.

Here when the weight rises 1 inch, B and C each shorten 1 inch and hence A lengthens 2 inches. That is, P is exerted

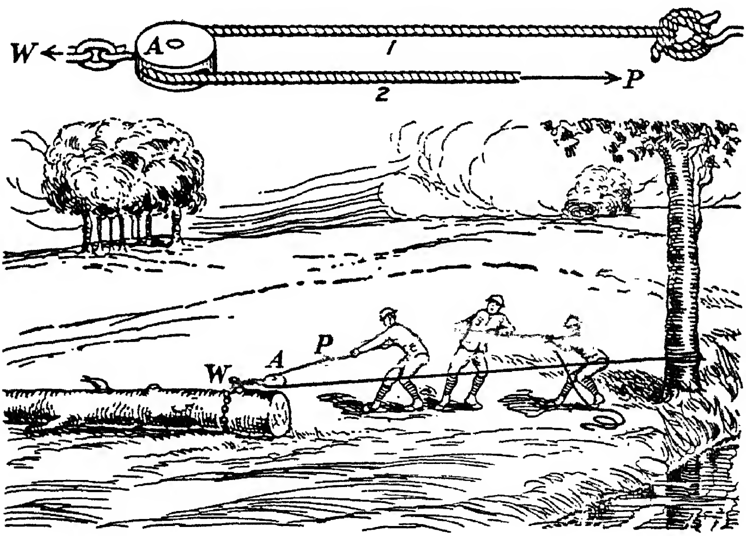


FIG. 162.—Illustrating the use of a single movable pulley. This arrangement is known as a "running tackle".

through twice the distance through which W rises, and the advantage $W/P = 2$, as before.

In Fig. 162 is seen a single movable pulley in use. Here three men can drag the log which with the arrangement in Fig. 158 required six.

147. Other Systems of Pulleys. To obtain greater mechanical advantage or to overcome various conditions, other combinations of pulleys may be used. Two are shown in Figs. 163, 164, the latter one being very common. In Fig. 163 the pulleys are arranged in tandem while in Fig. 164 they are mounted side by side.

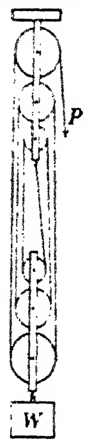


Fig. 163.—Combination of 6 pulleys; 6 times the force lifted.

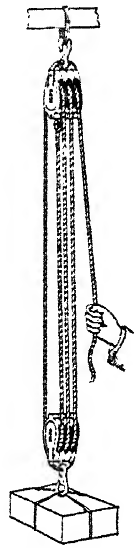


Fig. 164.—A familiar combination for multiplying the force 6 times.

Here there are six portions of the rope supporting W, and hence the tension in each portion is $\frac{1}{6}$ W.

$$\text{Hence, } P = \tfrac{1}{6}\, W,$$

or a force equal to $\frac{1}{6}$ W will hold up W. This entirely neglects friction, which in such a system is often considerable, and it therefore follows that, to prevent W from descending, less than $\frac{1}{6}$ W will be required. On the other hand, to actually lift W the force P must be greater than $\frac{1}{6}$ W. In every case friction acts to prevent motion.

Let us apply the principle of energy to this case. If W rises 1 foot, each portion of the rope supporting it must shorten 1 foot and the force P will act through 6 feet.

Then, work done on $W = W \times 1$ foot-pounds.
work done by $P = P \times 6$ foot-pounds.

These are equal, and hence

$$W = 6\,P$$

or $W/P = 6$, the mechanical advantage.

PROBLEMS

1. Find the mechanical advantage of the system shown in Fig. 165. This arrangement is called the Spanish Burton.

2. What fraction of his weight must the man shown in Fig. 166 exert in order to raise himself?

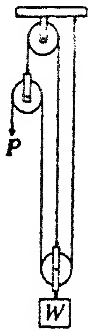


Fig. 165.—The Spanish Burton.

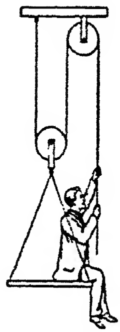


Fig. 166.—An easy method to raise one's self.

Fig. 167.—Find the pressure of the feet on the floor.

3. A man weighing 140 pounds pulls up a weight of 80 pounds by means of a fixed pulley, under which he stands (Fig. 167). Find his pressure on the floor.

4. Show how you would thread the rope through the pulleys in Fig. 163 to obtain a mechanical advantage of 5. (If necessary leave a pulley idle).

5. Comparing Figs. 158 and 162,

(*a*) What are the relative mechanical advantages of the "single whip" and the "running tackle"?

(*b*) Which needs the stronger rope? Which the stronger tree?

6. The men in Fig. 169 are dragging a gun towards a stone wall to which the pulley *B* is attached. Each man is exerting a force of 50 pounds. Neglecting friction, find (*a*) The force which the snub *C* must stand. (*b*) The tension in each rope. (*c*) The force acting on the gun mount. (*d*) The force which the wall must withstand.

7. Fig. 168 shows a hay-fork being used to lift hay from a wagon to a stack. If the load on the fork weighs 500 lbs. what pull must the team

exert? If the distance from the wagon to the car is 25 ft., what work is done by the team in raising the loaded fork? (Neglect friction.)

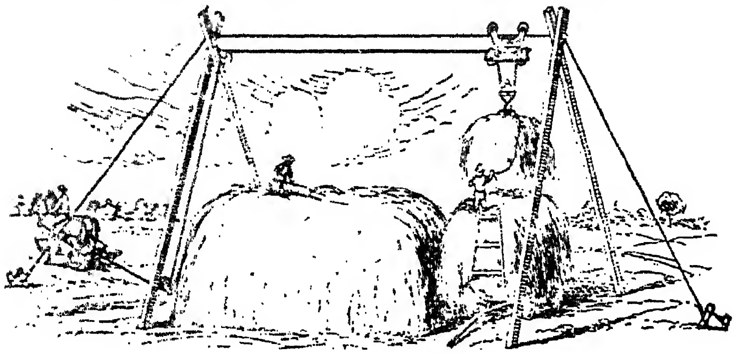


FIG. 168.—A hay-fork being used in building a stack.

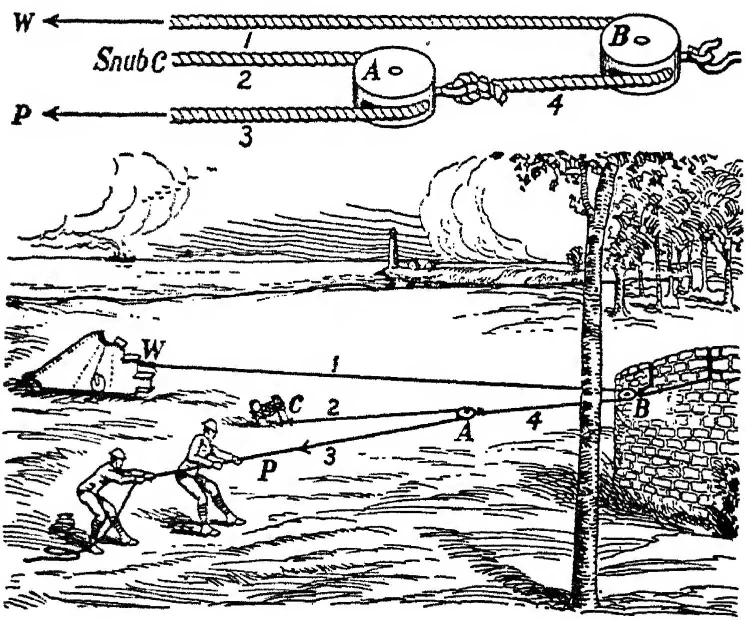
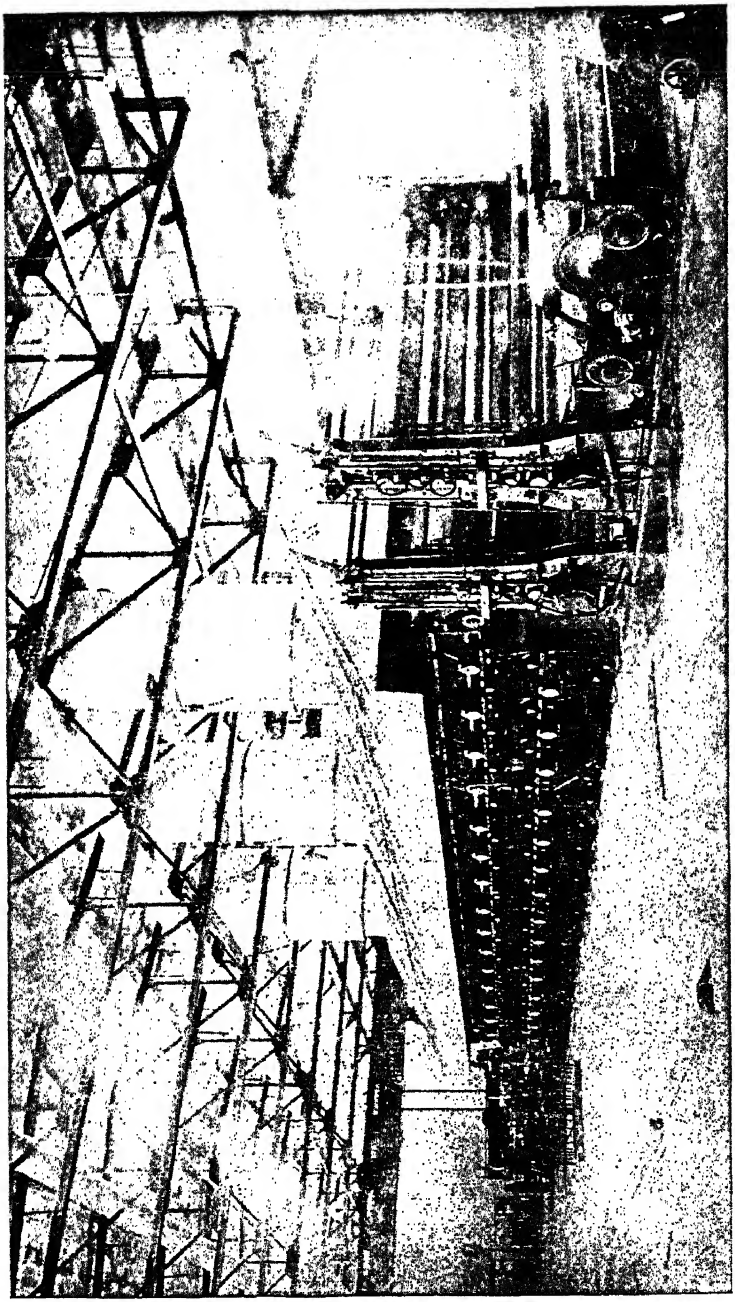


FIG. 169.—Two men using the arrangement of pulleys known as "whip on whip" to drag a heavy gun.

(Figs. 158, 162, 169 are from "Problems in Physics," published by the War Department, Washington, D.C.)

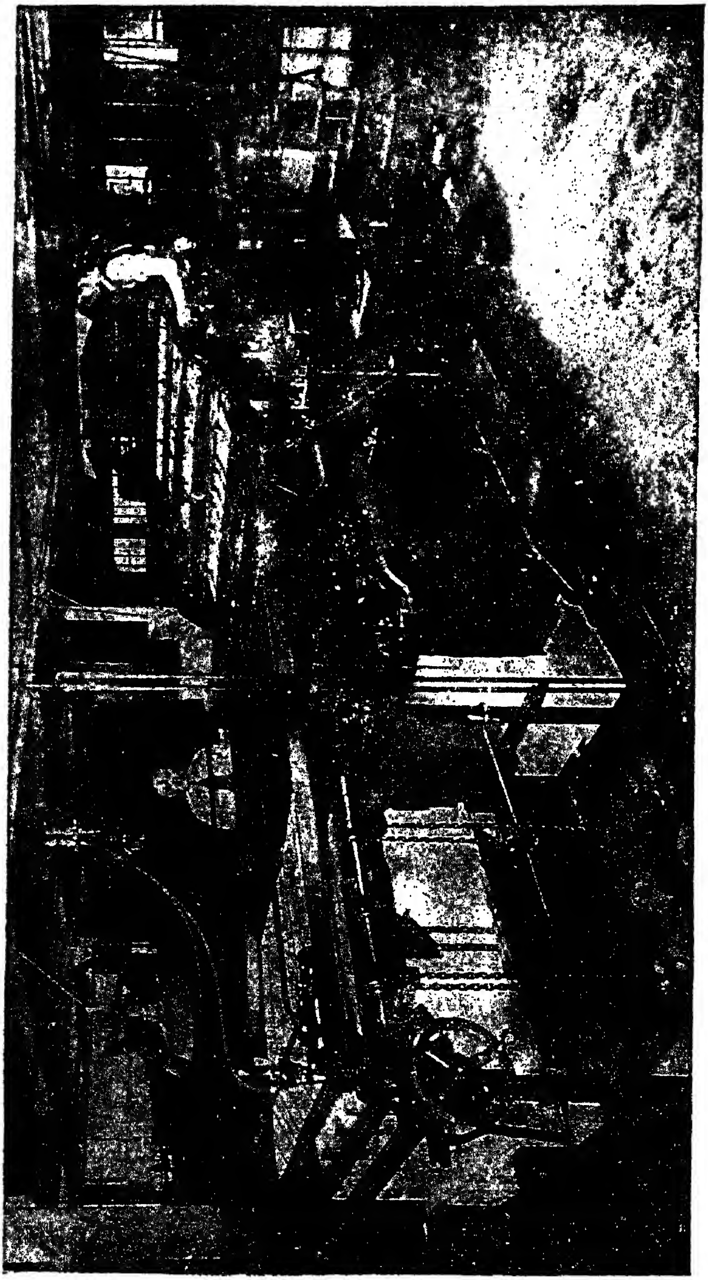


ING INE HORO ON

Plate 11

This is a portion of the machine by which the paper used in this book is made. Paper is made from various materials, the chief one being wood ground into pulp. After the pulpy mixture has been prepared it is run between and over numerous rollers and at last emerges in a long roll. The largest newsprint mill in the world is at Three Rivers, Quebec.

(Photograph supplied by Provincial Paper Mills)



PRINTING

• Plate 12

Above is the press on which this book is printed. The sheets of paper $31\frac{1}{2}$ x $44\frac{1}{2}$ in. in size are automatically fed in at the right-hand end and are made to encircle a cylinder which presses one face of the sheet upon the type on the bed of the machine. After this the sheets are led by means of tapes and deposited on the pile at the left-hand end.

CHAPTER XXV

WHEEL AND AXLE: INCLINED PLANE

148. Wheel and Axle. This machine is shown in Fig. 170. It is evident that in one complete rotation the weight P will descend a distance equal to the circumference of the wheel, while the weight W will rise a distance equal to the circumference of the axle. Hence

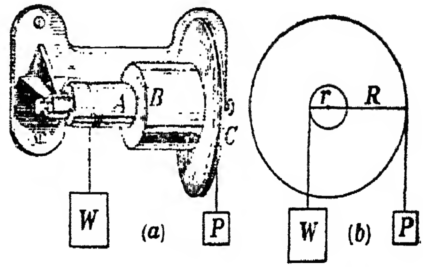


FIG. 170.—The wheel and axle. (a) general appearance; (b) diagram to explain its action.

$$P \times \text{circumference of wheel} = W \times \text{circumference of axle}.$$

Let the radii be R and r, respectively; the circumferences will be $2\pi R$ and $2\pi r$, and therefore

$$P \times 2\pi R = W \times 2\pi r, \text{ or } PR = Wr,$$

and the mechanical advantage, $W/P = R/r$.

149. Examples of Wheel and Axle. The windlass (Fig. 171) is a common example, but, in place of a wheel, handles are used. Forces are applied at the handles, and the bucket is lifted by the rope, which is wound about the axle.

FIG. 171.—Windlass used in drawing water from a well.

If P = applied force, and W = weight lifted,

$$\frac{W}{P} = \frac{\text{length of crank}}{\text{radius of axle}}$$

The capstan, used on board ships for raising the anchor, is another example (Fig. 172).

The sailors apply the force by pushing against bars thrust into holes near the top of the capstan. Usually the rope

is too long to be all coiled up on the barrel, so it is passed about it several times, and the end A is held by a man who keeps that portion taut. The friction is sufficient to prevent the rope from slipping. Sometimes the end B is fastened to a post or a ring on the dock, and, by turning the capstan, this portion is shortened and the ship is drawn into the dock.

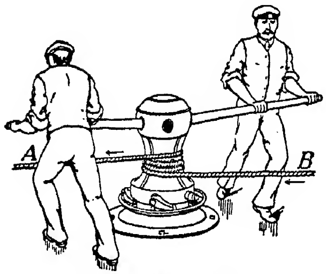


FIG. 172.—Raising the ship's anchor by a capstan.

150. Differential Wheel and Axle. This machine is shown in Fig. 173. It will be seen that the rope winds off one axle and on the other. Hence in one rotation of the crank the rope is lengthened (or shortened) by an amount equal to the difference in the circumferences of the two axles; but since the rope passes round a movable pulley, the weight to be lifted, attached to this pulley, will rise only one-half the difference in the circumferences.

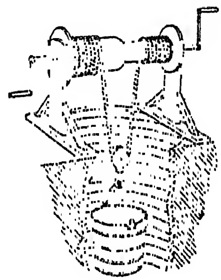


FIG. 173.—Differential wheel and axle.

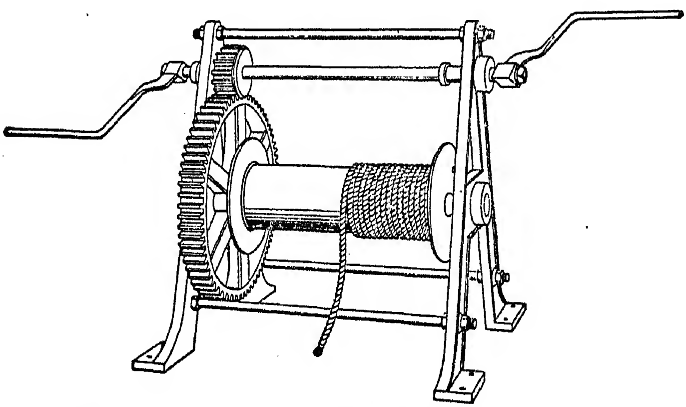


FIG. 174.—Windlass, with gearing, such as is used with a pile-driver.

It will be seen that by making the two drums which form the axles nearly equal in size, we can make the difference in their circumferences as small as we please, and the mechanical advantage will be as great as we desire.

The familiar and effective differential pulley is constructed on the principle of the wheel and axle.

PROBLEMS

1. A man weighing 160 lb. is drawn up out of a well by means of a windlass, the drum of which is 8 in. in diameter and the crank 24 in. long. (Fig. 171). Find the force required to be applied to the handle.

2. Calculate the mechanical advantage of the windlass shown in Fig. 174. The length of the crank is 16 in., the small wheel has 12 teeth and the large one 120, and the diameter of the drum about which the rope is wound is 6 in. If a force of 60 pounds be applied to each crank, how great a weight can be raised? (Neglect friction.)

151. Inclined Plane. If we wish to load a heavy box or barrel on a wagon it is often convenient to slide or roll it up a plank which has one end on the ground and the other on the wagon. The relation between the force exerted and the resistance overcome can be investigated by means of the apparatus shown in Fig. 175.

If W is the weight of the car C and P the applied force which will just make C move up the plane without acceleration, it is evident that P must act through a distance l in order that the car may rise a vertical distance h.

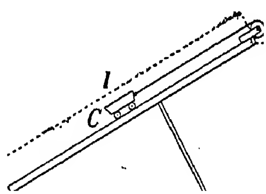


FIG. 175.—To show that $Pl = Wh$.

The work done by $P = Pl$, and the work accomplished $= Wh$.

From the principle of energy these should be equal if there were no friction.

Hence, $Pl = Wh$, or $W/P = l/h$,

or the theoretical mechanical advantage is the ratio of the length to the height of the plane.

If the angle at the foot of the inclined plane is 30°, $h = \frac{1}{2} l$, and $W/P = 2$ or $P = \frac{1}{2}W$. If we take into account the friction between the body and the inclined plane the mechanical advantage is less than l/h, since the force P must be greater then. By rolling the body up the plane instead of pushing or dragging it up the friction may be reduced.

152. The Screw. The screw consists of a grooved cylinder which turns within a hollow cylinder or nut which it just fits. The distance from one thread to the next is called the *pitch.*

The law of the screw is easily obtained. Let l be the length of the handle by which the screw is turned (Fig. 176) and P the force exerted on it. In one rotation of the screw the end of the handle describes the circumference of a circle with radius l, that is, it moves through a distance $2\pi l$, and the work done is therefore

$$P \times 2\pi l.$$

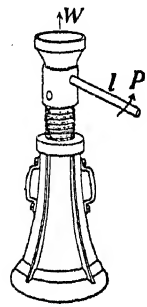


FIG. 176.—The jack-screw.

Let W be the force exerted upwards as the screw rises, and d be the pitch. In one rotation the work done is $W \times d$.

Hence, $$W \times d = P \times 2\pi l,$$

or $$W/P = 2\pi l/d,$$

or the mechanical advantage is equal to the ratio of the circumference of the circle traced out by the end of the handle to the pitch of the screw.

In actual practice the advantage is much less than this on account of friction.

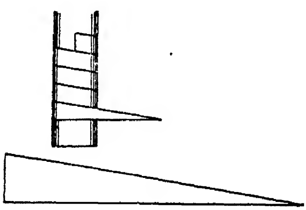
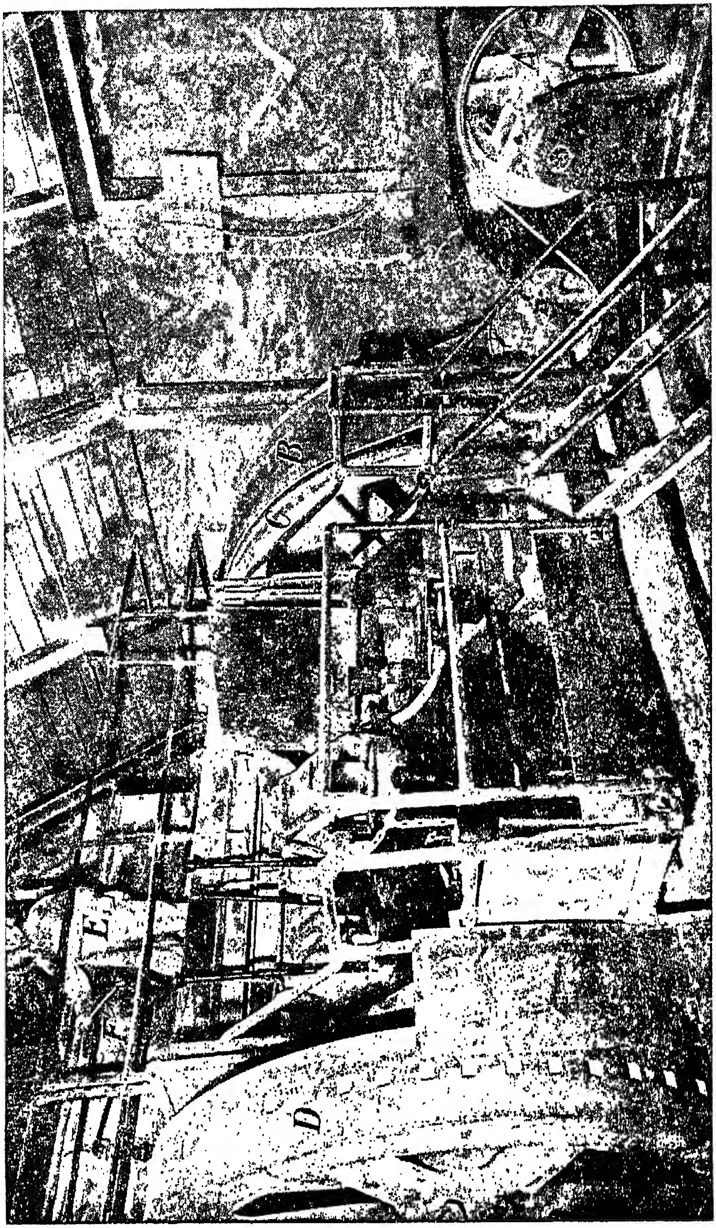


FIG. 177.—Diagram to show that the screw is an application of the inclined plane.

The screw is really an application of the inclined plane. If a triangular piece of paper, as in Fig. 177, be wrapped about a cylinder (a lead pencil, for instance), the hypotenuse of the triangle will trace out a spiral like the thread of a screw.



W- NES

Plate 13

• Plate 13

This powerful machine is 2,900 ft. below the surface and crushes the ore into pieces about 6 inches through. The jaw-crusher opening is 48 in. x 60 in. The jaws are 60 in. wide and 96 in. deep. The swing jaw is directly under the operator *E*. Power is supplied by an electric motor behind the pulley *A* which is mounted on an extension of the rotor shaft of the motor. The power is transmitted from the pulley *A* by the belt *B* to the crusher drive-pulley *C*, 10 ft. in diameter with a 38-in. face. The fly-wheel *D* has a diameter 10 ft. and face 12 inches. The lever *F* controls an air cylinder which opens a gate to allow the ore to pass into the crusher. The ore flows down an inclined chute into the crusher opening which is back of the man *E*. The discharge from the crusher drops 150 ft. to the 3,050 ft. level where it is drawn out into the skips which take it up to the surface where it is further crushed to 3/16 inch. This crusher is one of the largest in Canada.

(Photograph taken specially for this book by the Hollinger Mines)

Examples of the screw are seen in the letter press (Fig. 178) and the mechanic's vice (Fig. 179).

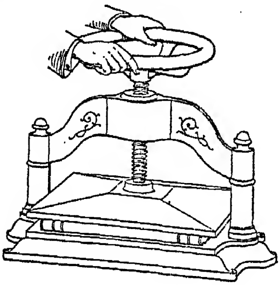


Fig. 178.—The letter press.

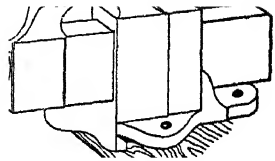


Fig. 179.—The mechanic's vice.

ILLUSTRATIVE PROBLEMS

1. Why should shears for cutting metal have short blades and long handles?

2. In the driving mechanism of a self-binder, shown in Fig. 180, the driving-wheel A has a diameter of 3 ft., the sprocket-wheels B and C have 40 teeth and 10 teeth, respectively. The large gear-wheel D has 37 teeth and the small one E has 12 teeth, and the crank G is 3 in. long. Neglecting friction, what pull on the driving-wheel will be required to exert a force of 10 pounds on the crank G? (Find the number of revolutions of the crank for one revolution of the driving-wheel and apply the principle of energy.)

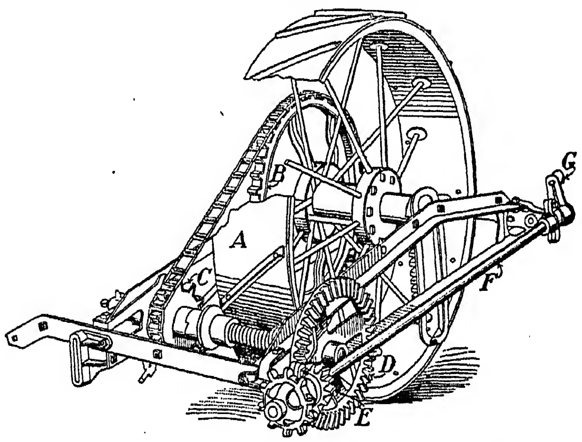


Fig. 180.—The driving part of a self-binder. The driving-wheel A is drawn forward by the horses. On its axis is the sprocket-wheel B, and this, by means of the chain, drives the sprocket-wheel C. The latter drives the cog-wheel D which, again, drives the cog-wheel E, and this causes the shaft F with the crank G on its end to rotate.

3. Fig. 181 shows a three-horse evener used when three horses are to be attached to a binder or other farm implement.

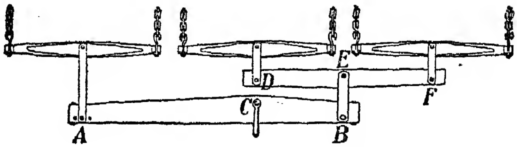
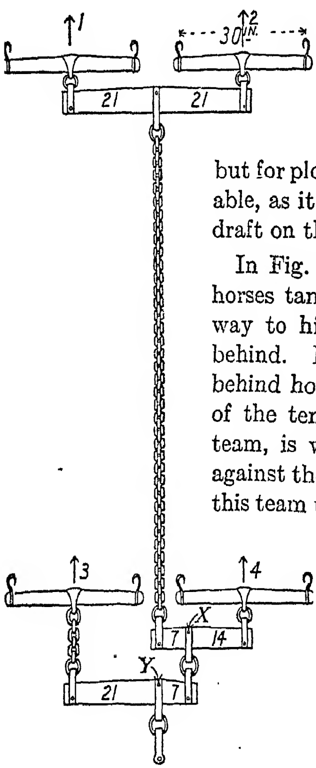


Fig. 181.—A three-horse evener.

(*a*) If $AC = 40$ in. and $CB = 19$ in., find the pulls exerted by the single horse at A and by the team at B to overcome a resistance of 295 lbs at C.

(*b*) If $DE = 21$ in. and EF – 19 in., find the pulls exerted by the horses attached at D and F.

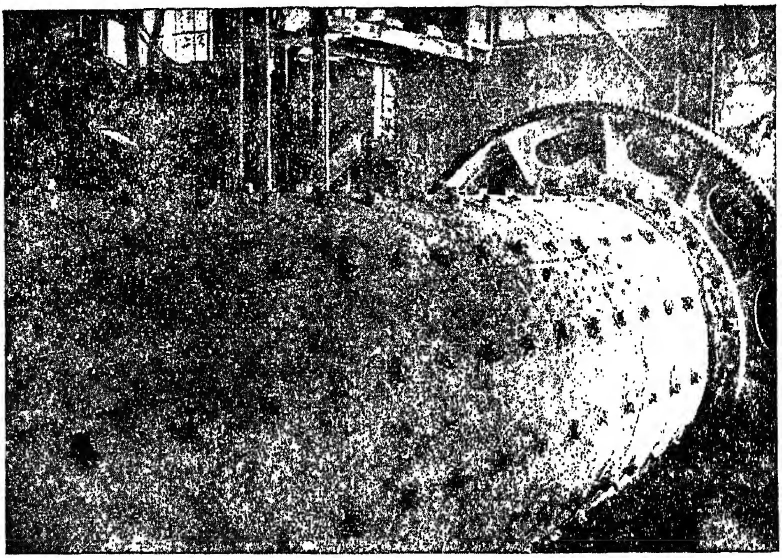


4. For some operations on the farm it is economical to use teams having 4, 5 or more horses. They may be hitched abreast or in a tandem manner. For harrowing, cultivating and seeding, the former method may be used, but for ploughing the tandem arrangement is preferable, as it either completely, or largely, avoids side draft on the implement.

In Fig. 182 is shown how to hitch two pairs of horses tandem, while in Fig. 183 is illustrated the way to hitch five horses, three in front and two behind. In the latter case, horse 5 trails directly behind horse 3 in the furrow, and a small portion of the tension in the chain, exerted by the front team, is wasted in pushing the plough sidewise against the wall of the furrow, while the reaction on this team tends to push the team to the right toward the ploughed land. In the five-horse hitch illustrated, this side-force is not great enough to cause trouble.

(*a*) In Fig. 182 let each horse exert a pull of 100 pd. What is the total pull on the pin Y and hence on the plough? Show that the pull of horse 4 balances about pin X the pull of 1 and 2 together; and that the pull of horse 3 balances about Y the combined pull of 1, 2 and 4.

Fig. 182.—A four-horse tandem hitch, suitable for a heavy wagon or a sulky plough. The arrows show the direction the horses pull.



BALL MILL (ABOVE), TUBE MILL (BELOW)

These are two steps in the recovery of gold by the cyanide process. The principle of this method is illustrated in Plate 15 and a brief description is given on the back of Plate 16. There are seven ball mills and fourteen tube mills at the Lake Shore Mines, Kirkland Lake, Ont.

(Diagram in Pl. 15 and photographs of Plates 14, 16, 17 18 supplied by Lake Shore Mines)

Plate 14

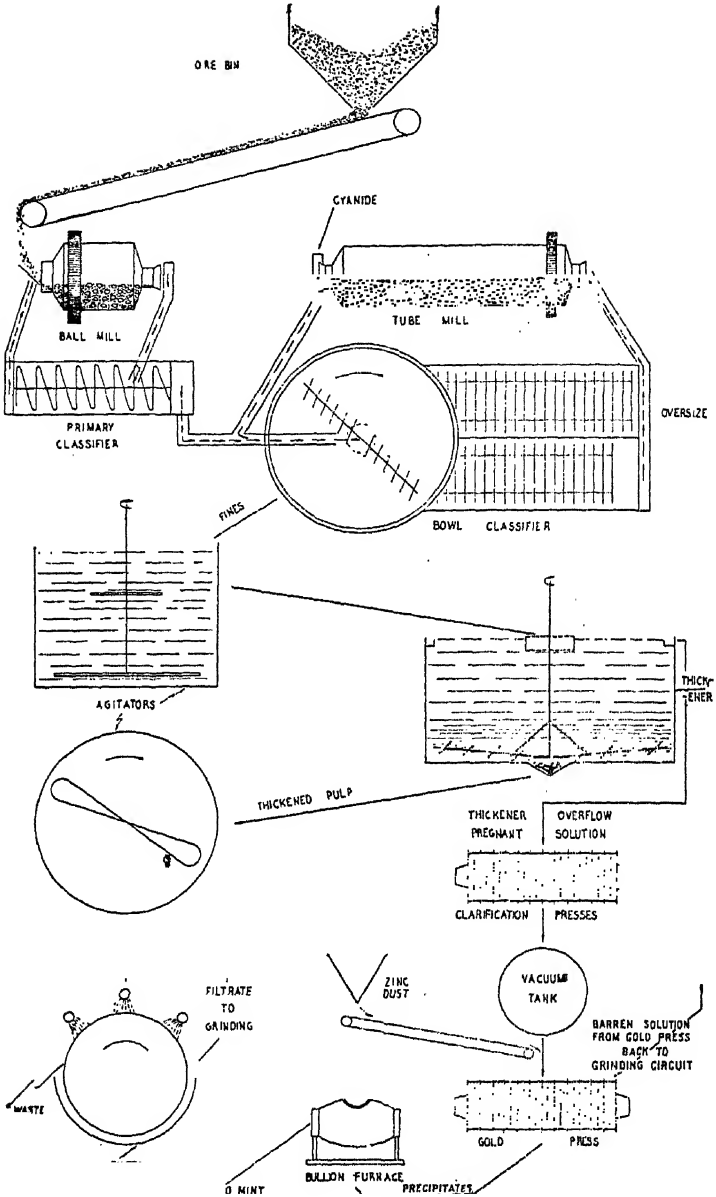
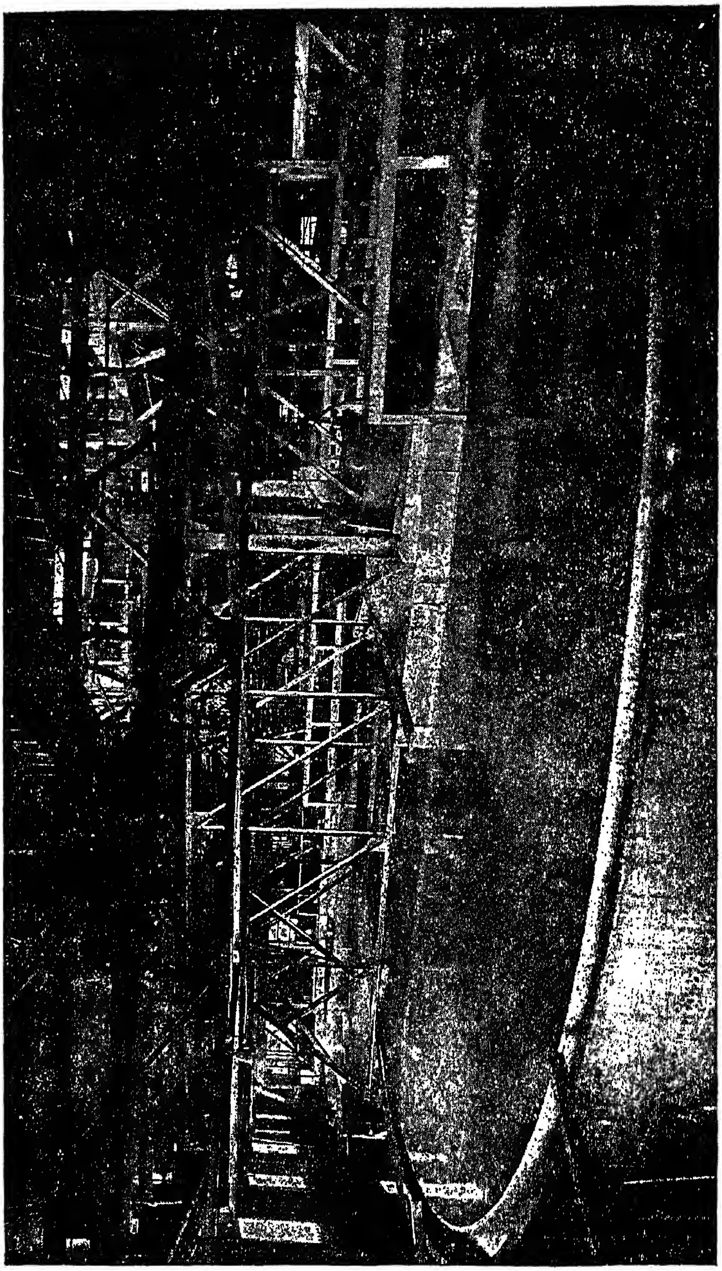


DIAGRAM TO ILLUSTRATE THE CYANIDE PROCESS OF TREATING GOLD ORE

Plate 15



THICKENING OR DECANTATION TANK

● **Plate 16**

Diameter, 50 ft.; depth, 12 ft. There are six such tanks at Lake Shore Mines.

THE CYANIDE PROCESS

Most of the gold mined in Canada is found in the form of very fine particles within solid granite rock and it is recovered by what is known as the cyanide process.

The ore, after being crushed to small fragments, goes into the Ore Bin (Pl. 15) and thence is carried by a belt to the Ball Mill, which contains a solution of potassium cyanide or of sodium cyanide. The Ball Mill shown in Pl. 14 is 7 ft. in diameter and 6 ft. long and rotates 24 times a minute. In it are 4-inch steel balls which continually fall upon the ore and grind it to powder. From this it passes into the Primary Classifier (the trough seen in front of the Ball Mill). The finer material stays in suspension in the solution while the coarser grains sink to the bottom and are returned to the mill to be ground finer.

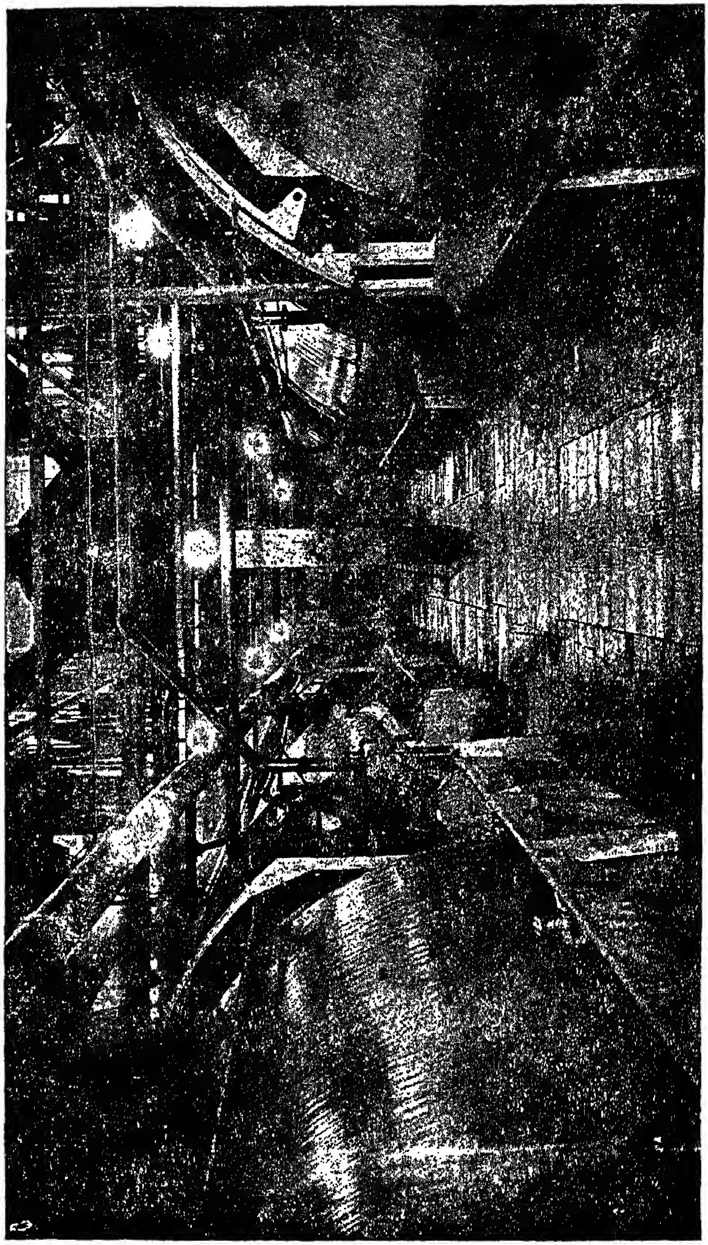
The grinding is continued in the Tube Mill. That shown in the picture is 5 ft. in diameter and 16 ft. long and rotates 30 r.p.m. and in it are iron balls 1¾ in. in diameter. The products from it go into the Bowl Classifier which further separates the finer particles from the coarser grains and returns the latter to the Tube Mill for more grinding.

The solution holding the fine particles now passes into the Agitators which stir it up while oxygen is bubbled through it. In this way the gold is made to combine chemically with the cyanide.

In the immense Thickening Tank (Pl. 16) a rake near the bottom, driven by the wheel seen spinning at the centre, rakes the settled or thickened pulp to the centre of the tank where it is pumped out. Other pulp enters from above at the centre and the almost clear solution, which contains nearly all the gold, overflows the edge of the tank and passes to the Clarification Press, where the solution is forced through canvas and is cleared of colloidal material. It then goes to the Vacuum Tank where all gases are drawn out of the solution, including the oxygen which was needed to dissolve the gold, but now that the gold is to be precipitated the oxygen must be removed.

Next, fine zinc dust is added to the solution. The zinc replaces the gold in solution and the gold precipitates as a fine brown-black powder which is caught by passing the solution through the Gold Press, similar to the previous Clarification Press. The precipitates are melted in an oil-fired Bullion Furnace, refined and poured into moulds and come out as gold bars.

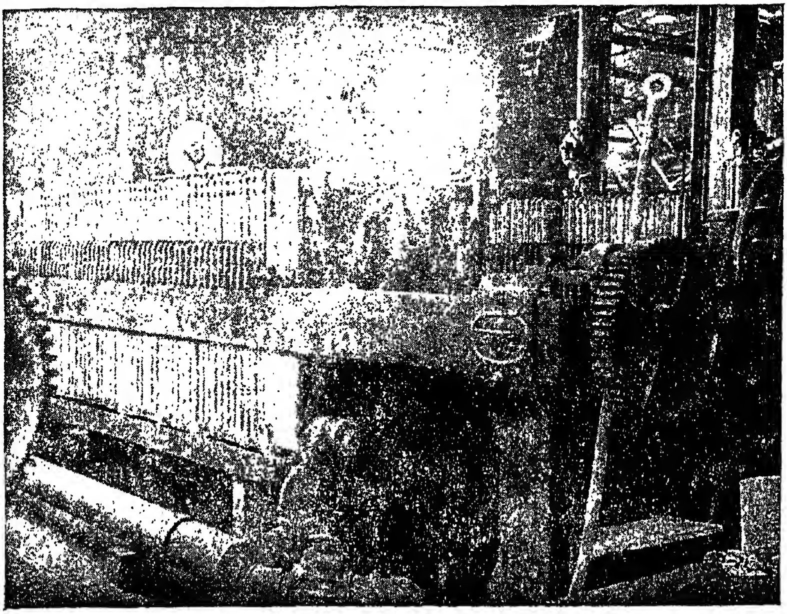
Some of the gold has however been left behind in the Thickening Tank. The pulp containing it is sent to the Agitators and fresh cyanide and lime are added. After a long period of agitation the pulp goes to the Filters (Pl. 17) by means of which nearly all the remaining gold is recovered. The filtrate, which is not rich enough to precipitate, is sent back to be used as grinding solution in the Ball and Tube Mills.

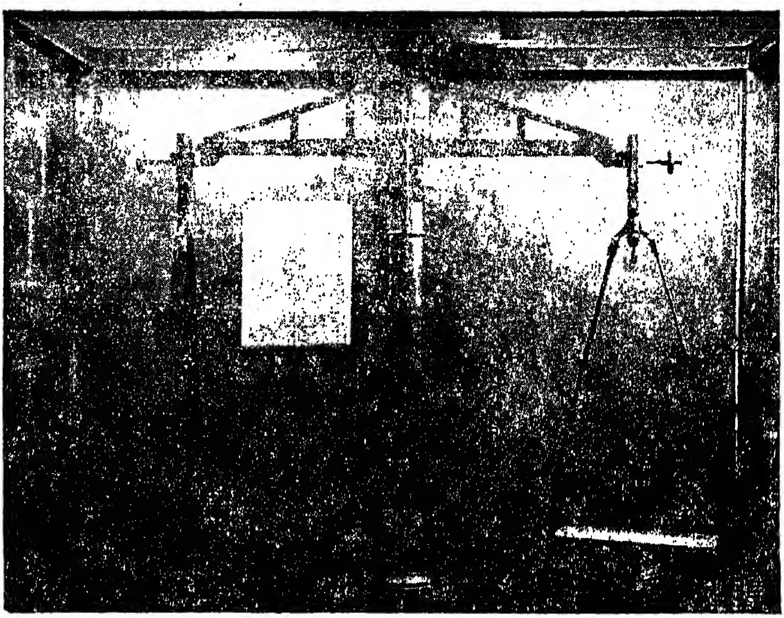


DRUM-TYPE FILTERS

Plate 17

Diameter 14 ft., length 14 ft. These filters separate the less rich solution from the waste material. The drum revolves once in three minutes.





Clarification Press (above), Gold Brick being weighed (below).
Approximate weight 1,300 oz. troy, or 89 lb. avoirdupois.
In the press the solution is forced by pressure through canvas.

(*b*) In Fig. 183 let each horse in the front team exert a pull such that the entire tension in the chain is 300 pd. This tension does two things:

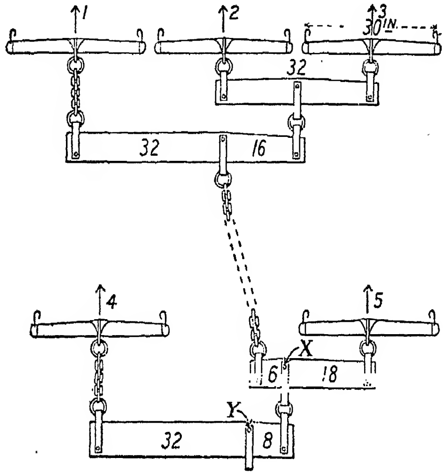


Fig. 183.—A five-horse tandem hitch suitable for a sulky plough.

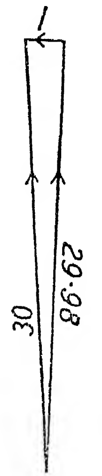


Fig. 184.—Triangle of forces.

it displaces the plough forward in the direction of the furrow and pulls the plough to the left against the wall of the furrow. Let the length of the chain be 10 ft. or 120 in., and let the forward end be deflected 4 inches to the left from being in a line parallel to the furrow. Let us draw a triangle (Fig. 184) with one side parallel to the chain, a second parallel to the furrow and the third at right angles to the latter. Then, the first and third sides of this triangle will be in the ratio of 120 to 4 or 30 to 1, and (by calculation) the third one is 29.98. Hence from the figure, if the tension of the chain is 300 pd., the cross-force is 10 pd. Show that horse 5 balances about X horses 1, 2, 3, and that horse 4 balances about Y horses 1, 2, 3, 5; also that horses 5 and 4 do not exert quite 100 pds.

(Fuller information about multiple horse hitches, including "tie-ins" and "buck-straps" to ensure that all horses pull evenly, may be obtained from the Ontario Agricultural College, Guelph, Ont.)

PART IV—SOME PROPERTIES OF MATTER

CHAPTER XXVI

THE MOLECULAR THEORY OF MATTER

153. Molecules and Atoms. Every day we handle matter in the form of solids, liquids and gases, and we often wonder just what it is made up of. Centuries of thought and experiment have led to the general belief that it is composed of minute separate particles. These ultimate particles of a substance are called **molecules.** Some molecules can still further be divided into **atoms,** but their nature is then entirely changed. Thus a molecule of water may be divided into two atoms of hydrogen and one of oxygen, while an oxygen molecule consists of two atoms of oxygen. The very atoms themselves have been submitted to close investigation during the last quarter-century and some remarkable facts about them have been disclosed. Reference to these will be made in §164 and in the last chapter of this book.

154. Evidence suggesting Molecules. Various experiments suggest the existence of molecules:

Experiments.—1. Place beans or peas in water in a saucer; they expand and the water disappears.

2. When a row-boat is put in the water it may leak freely, but in a day or two the wood has swollen and the seams are closed.

3. Water and alcohol are practically incompressible liquids, but on mixing together 50 c.c. of each the result is not 100 c.c., but about 97 c.c.

4. When copper and tin are melted together in the ratio of 2 of copper to 1 of tin they produce an alloy much used in optics as it takes a fine polish and does not tarnish readily, and there is a shrinkage in volume of 7 or 8 per cent.

5.(*a*) Various gases may be inclosed in the same space; indeed it is hard to obtain a pure gas. (*b*) Fish live by the oxygen gas which is dissolved in the water. (*c*) Household ammonia is simply ammonia gas dissolved in water; and in making "soda water" carbon dioxide gas is forced into water under great pressure.

A simple explanation of these phenomena is that all bodies are made up of molecules with spaces between, into which the molecules of other bodies may enter. As we shall see, the molecules and the spaces between are much too small to be observed with our most powerful microscopes. The magnifying power would have to be increased at least a thousand times, but even if this magnification were obtained, it is probable that the molecules could not be seen, since there are good grounds for believing that they are constantly moving so rapidly that the eye could not follow them.

155. Diffusion of Gases. The intermingling of molecules is best illustrated in the behaviour of gases. In order to investigate this question the French chemist, Berthollet, used apparatus like that illustrated in Fig. 185. It consisted of two glass globes provided with stopcocks, which could be securely screwed together. The upper one was filled with hydrogen and the lower with carbon dioxide, which is 22 times as dense. They were then screwed together, placed in the cellar of the Paris Observatory and the stopcocks opened. After some time the contents of the two globes were tested and found to be identical,—the gases had become unimixed.

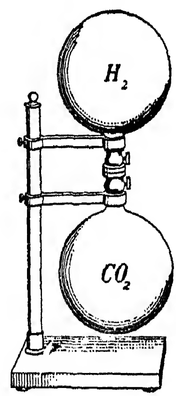


Fig. 185.—Two glass globes, one filled with hydrogen, the other with carbon dioxide. The two gases mix until the contents of the two globes are identical.

When the passage connecting the two vessels is small, hours may be required for perfect mixing; but when it is large, a few minutes will suffice.

A simpler experiment on diffusion is the following:

Fill one wide-mouthed jar or bottle with hydrogen and a similar one with oxygen, which is 16 times as heavy, covering the vessels with glass plates. Then put them together as shown in Fig. 186 and withdraw the glass plates. After allowing them to stand for some minutes separate them and apply a match. At once there will be a similar explosion from each, showing that the two gases have become mixed.*

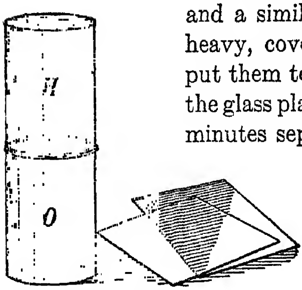


Fig. 186.—Hydrogen in one vessel quickly mixes with oxygen in the other.

It is through diffusion that the proportions of nitrogen and oxygen in the earth's atmosphere are the same at various elevations. Though oxygen is the heavier constituent, there is no excess of it at low levels.

156. Diffusion of Liquids and Solids. Liquids diffuse into each other, though not nearly so rapidly as do gases. The following experiments illustrate this:

1. Carefully pour coloured alcohol (sp. gr. 0·8) on the top of clear water in a tumbler (or introduce water under the alcohol); the mixing of the two will be seen to commence at once and will proceed quite rapidly.

2. Let a wide-mouthed bottle *a* (Fig. 187) be filled with a solution of copper sulphate and then placed in a larger vessel containing clear water. The solution is denser than the water, but in time the colour will be distributed uniformly throughout the liquid.

Fig. 187.—Copper sulphate solution in a bottle, placed in a vessel of water. In time the blue solution spreads all through the water.

Diffusion takes place also in some metals though very slowly at ordinary temperatures. If discs of gold and lead are kept pressed together for some weeks there will be an appreciable diffusion of gold through the solid lead.

If a lump of sugar is dropped into a cup of tea, it soon dissolves, and in time its molecules spread to every part of

*In performing this experiment wrap a cloth about each jar for safety.

the liquid, giving sweetness to it. In this instance the molecules of water enter into the lump of sugar and loosen the bonds which hold the molecules of sugar together. The molecules thus set free spread throughout the liquid.

Ice gradually disappears, even when below the melting point. The pavement is sometimes dangerous to walk or drive on, but in a few hours, even on a cold day, enough of the ice may disappear to allow one to move safely over it. Camphor and iodine are solids which when gently heated readily pass into vapour without melting. Solid carbon dioxide, or "dry ice," has now become quite common as a refrigerant, being especially convenient in shipping ice cream. At a temperature of $-78°$ C. it simply turns into gas. To form hoar frost vapour changes directly into solid.

The motions of the molecules of a solid are much less free than those of a liquid. They vibrate back and forth about their mean positions, but as a rule are kept well to their places by their neighbours, although there may be an interchange of atoms among the molecules. When heated, the molecules are more vigorously agitated and the body expands, and if the heating is intense enough, it becomes liquid.

When a solid changes to a liquid its volume is not greatly changed and we conclude that in these two states of matter the molecules are about equally close together. But in gases they are much farther apart. A cubic centimetre of water when turned into steam occupies about 1700 c.c.

157. Cohesion and Adhesion. When we attempt to separate a solid into pieces, we experience difficulty in doing so. The particles cling together, refusing to separate unless compelled by a considerable effort. This attraction between the molecules of a body is called **cohesion**, and the molecules must be very close together before this force comes into play. The fragments of a porcelain vessel may fit together so well that the eye cannot detect any cracks, but the vessel falls to pieces at the touch of a finger.

Some substances can be welded together much more easily than others. Clean surfaces of metallic lead, when pressed together, cohere so that it requires considerable force to pull them apart; and powdered graphite (the substance used in "lead"-pencils), when submitted to very great pressure, becomes once more a solid mass.

Cohesion is the natural attraction of the molecules of a body for one another. If the particles of one body cling to those of another body, there is said to be **adhesion** between them. Mud sticks to our shoes and chalk to the blackboard. The forces in the two cases are of the same nature, and there is really no good reason for making a distinction between them. Indeed, it may be added that regarding the real nature of these forces we are entirely ignorant.

The force of cohesion is also present in liquids, but it is much weaker than in solids. If a clean glass rod is dipped in water and then withdrawn, a film of water will be seen clinging to it; but if dipped in mercury, no mercury adheres. This shows that the adhesion between glass and water is greater than the cohesion between the molecules of water, but the reverse holds in the case of mercury and glass.

158. Viscosity. If one tilts a vessel containing water, it soon comes to its new level. With ether or alcohol the new level is reached even more quickly, but with molasses much more slowly.

Although the molecules of a liquid or of a gas move with great freedom amongst their fellows, some resistance is encountered when one layer of the fluid slides over another. It is a sort of internal friction and is known as **viscosity.** Ether and alcohol have very little viscosity; they flow very freely and are called mobile liquids. On the other hand, tar, honey and molasses are very viscous.

Let us stir the water in a basin vigorously and then leave it to itself. It soon comes to rest, showing that water has

viscosity. The viscosity of gases is smaller than that of liquids, that of air being about $\frac{1}{80}$ that of water.

For lubricating purposes an oil must have a certain "body," which depends on its viscosity, and it should be suited to the bearing in which it is used. If the bearing supports great pressure the oil should be so viscous that it will not all be squeezed out. There should always be a layer of oil between the surfaces which run together. Kerosene (coal oil) would simply leak away. Since viscosity decreases with the temperature, the oil used in the cylinder of a gasoline engine should be more viscous than that used in an ordinary bearing in a machine. Further, the motorist uses a less viscous oil in winter than in summer. A heavy oil in winter makes the pistons stick in the cylinders so that it is difficult to start the engine.

The viscosity of a liquid is measured by observing the time required for a certain volume of the liquid to flow, under stated conditions as to head, through a short tube of small bore. In the Saybolt Universal Viscosimeter the tube is 0·483 in. long and its diameter is 0·0695 in., and the time in seconds for 60 c.c. to flow through the tube is the viscosity in "sec. Saybolt." For automobiles, in place of specifying the oil as "light," "medium" and "heavy" it is common practice to use a number suggested by the Society of Automotive Engineers (S.A.E.). It is found that S.A.E. No. 10 corresponds at 130° F. to sec. Saybolt 90-115, No. 20 to 120-150, No. 30 to 185-220, etc.

159. Distinction between Solids and Liquids. We readily agree that water is a liquid and that glass is a solid, but it is not easy to frame a definition which will discriminate between the two kinds of bodies. A liquid offers no *permanent* resistance to forces tending to change its shape. It will yield to even the smallest force if continuously applied, but the rate of yielding varies greatly with different liquids, and it is this temporary resistance which constitutes viscosity.

Experiments. 1. Drive two pairs of nails in a wall in a warm place, and on one pair lay a stick of sealing-wax or a paraffin candle, on the other a tallow candle or a strip of tallow (Fig. 188). After some days (perhaps weeks), the tallow will still be straight and unyielding while the wax will be bent.

FIG. 188.—A paraffin candle bends but a tallow one keeps straight.

2. Lord Kelvin placed several corks on the of the water in a tall jar. On these he

laid a large cake of shoemakers' wax about two inches thick, and on top of this again were put some lead bullets. Six months later the corks had risen and the bullets had sunk half through the cake, while at the end of the year the corks were floating in the water at the top and the bullets were at the bottom of the vessel. Try this experiment.

These experiments show that at ordinary temperatures wax is a liquid, though a very viscous one, while tallow is a true solid.

160. Kinetic Theory of a Gas. The laws followed by gases are much simpler than those of solids and liquids, and are satisfactorily accounted for by the motions of the molecules of the gas. In a gas these ultimate particles are practically independent of their neighbours, moving freely about in the vessel containing the gas. They continually rush from side to side, frequently colliding with one another. The never-ceasing striking of the molecules of the gas against a body give rise to the pressure exerted by the gas. This view of a gas is known as the Kinetic Theory.

FIG. 189.—Illustrating the motions of the particles of a gas.

Experiment. These motions are neatly illustrated in the apparatus shown in Fig. 189. It consists of a pyrex glass tube containing a small amount of mercury on the surface of which lies a quantity of crushed blue glass. The tube is highly exhausted of air. On heating it with a gas flame or an electric heater the mercury readily boils and mercury vapour is driven off with high velocity. The molecules of the vapour carry before them the particles of glass, which fly about in the space above the mercury, colliding together and striking the sides of the tube. The effect is rendered more vivid if the light from an intense source, such as an arc lamp, is projected upon the tube.

It is clear that if one reduces the volume of the vessel containing the gas the strokes of the molecules against the surface will be more numerous and the pressure will be increased (Boyle's Law, § 66).

If a partially inflated football bladder is placed in an oven and gently heated, it expands, showing that the pres-

sure exerted by a gas is greater as its temperature rises. Evidently, when the gas is heated, its molecules move faster and produce a greater pressure.

The speed of these molecules is enormous. At atmospheric pressure and freezing temperature the average speeds are: Hydrogen, 6,032 ft. per sec.; nitrogen, 1,618 ft.; oxygen, 1,514 ft.; carbon dioxide, 1,291 ft. The heavier the gas, the slower its particles move.

161. Passage of Hydrogen through a Porous Wall. As the velocities of the hydrogen molecules are so great, they strike much more frequently against the walls of the vessel which contains them than do the molecules of other gases. Hence it is harder to confine hydrogen in a vessel than another gas, and it diffuses more rapidly. This is well illustrated in the following way:

Experiment. An unglazed earthenware cup *A* is closed with a rubber, or other, air-tight stopper, and a glass tube connects this with a bottle nearly full of water (Fig. 190). A small glass tube *B*, drawn to a point, also passes through the cork of the bottle and reaches nearly to the bottom of the bottle.

Now hold over the porous cup a bell-jar full of dry hydrogen, or pass illuminating gas by the tube *C* into the bell-jar. Very soon a jet of water will spurt from the tube *B*, sometimes with considerable force. After this action has ceased, remove the bell-jar, and bubbles will be seen entering the water through the lower end of the tube *B*.

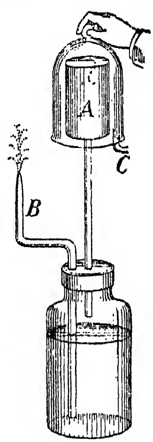


FIG. 190.—Experiment showing rapid passage of hydrogen through a porous wall.

At first the space within the porous cup and in the bottle above the water is filled with air, and, when the hydrogen is placed about the porous cup, its molecules pass in through the walls of the cup much faster than the air molecules come out. In this way the pressure within the cup is increased, and this, when transmitted to the surface of the water, forces it out in a jet. When the jar is removed, the hydrogen rapidly escapes through the porous walls, and the air rushing in is seen to bubble up through the water.

162. Osmosis. Experiment. Over the opening of a thistle-tube let us tie a sheet of moistened parchment or other animal membrane (such as a piece of bladder). Then having filled the funnel and a portion of the tube with a strong solution of copper sulphate, let us support it, as in Fig. 191, in a vessel of water, so that the water outside is at the same level as the solution within the tube.

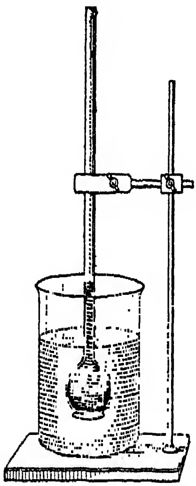


FIG. 191.—Osmosis.

In a few minutes the solution will be seen to have risen in the tube. The water will appear blue, showing that some of the solution has come out; but evidently more water has entered the tube. The rise in level continues (perhaps for two or three hours) until the hydrostatic pressure due to the difference of levels stops it.

In place of the glass funnel the apparatus shown in Fig. 192 may be used. *A* is a hollow metal hemisphere with a flange on the open side. By means of the ring *B*, which may be screwed tightly to the flange, any desired membrane may be stretched across the open side of the hemisphere and made water-tight by rubber washers. A glass tube is attached by means of rubber tubing to the nipple *C*. Molasses may be used in place of copper sulphate.

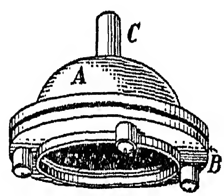


FIG. 192.—Alternative apparatus.

This mode of diffusion through membranes is called **osmosis,** and the difference of level thus obtained is called **osmotic pressure.**

Substances such as common salt and others which usually form in crystals are called **crystalloids.** These diffuse through membranes quite rapidly. Starch, gelatine, albumen and gummy substances generally, which are usually amorphous in structure, are called **colloids.** These diffuse very slowly.

Osmosis plays an important part in the processes of nature.

CHAPTER XXVII

THE MOTIONS AND THE NATURE OF THE MOLECULES

163. Evidence of Motion of the Molecules. One would like actually to see the molecules, but they are so small and move so fast that the most powerful microscope will not directly reveal them. But some strong indirect evidence of their existence and motions has been obtained.

Experiments. 1. The little apparatus shown in Fig. 193 is first clamped on the stage of a microscope multiplying 50 to 100 diameters. Then by means of the bulb A the chamber B is filled with smoke, which is then illuminated by directing a beam of light (preferably from an arc lamp) through the window C.

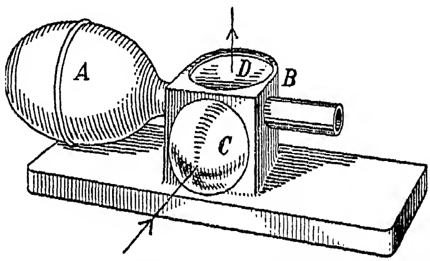


FIG. 193.—Apparatus to show motions of the molecules.

The observer now looks through the microscope down through the window D. The particles of smoke appear like so many bright point-sources of light and they dart about in a fascinating way. Why do they do this? It is believed that the molecules of air in the chamber knock them about.

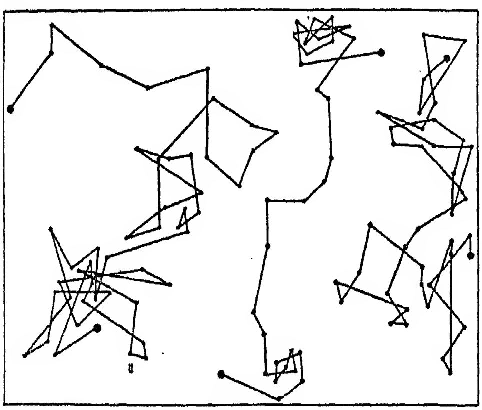


FIG. 194.—Typical Brownian movements.

2. Place on a glass plate some rosin dissolved in alcohol and mixed with water; or some soot, or gum mastic, or mercuric sulphide, in water. Then place any one of these plates under a powerful microscope. The little particles of matter held in the liquid are seen to quiver and dart about in a peculiar haphazard way, as shown in Fig. 194.

These motions are easily observed and are believed to be due to impacts by the molecules of the liquid.

Such observations were first made by an English botanist named Brown in 1827 and are known as Brownian movements.

The spaces between the molecules of a liquid are much smaller than in a gas, and so their collisions are much more frequent. Moreover, the molecules exert an attractive force on one another, the force of cohesion, but they glide about from point to point throughout the entire mass of the liquid. Usually when a molecule comes to the surface, its neighbours hold it back and prevent it from leaving the liquid. The molecules, however, have not all the same velocity, and occasionally, when a quick-moving one reaches the surface, the force of attraction is not sufficient to restrain it and it escapes into the air. We say the liquid **evaporates.**

When a liquid is heated, the molecules are made to move more rapidly and the collisions are more frequent. The result is that the liquid expands and also the evaporation is more rapid.

In the case of oils the molecules appear to have great difficulty in escaping at the surface, and hence there is little evaporation.

164. The Electrical Structure of Matter. In 1895 the X-rays were discovered and their applications in medicine have rendered them well known. In the following year it was discovered that some substances, such as compounds of the element uranium, continually gave off radiations which could pass through opaque wrapping and fog a photographic plate, much as X-rays do. The power to do this is called radioactivity. It is discussed in the last chapter.

Since their discovery an immense amount of scientific investigation has been made into the nature of the X-rays and of radioactivity and, on the other hand, they have been used to search into the structure of matter. By the use of

X-rays and radioactivity it has been possible to explore the region of the molecules, to break the molecules into atoms, to knock the atoms to pieces and to reveal their structure.

From these investigations we have learned that there are 92 different elements and almost certainly no more, and that the elements may be arranged in a definite series, or order, which shows their relations one to the other.

The atoms are made up of two sorts of bits of material, which have been named **protons** and **electrons**. These appear to be the very building stones of matter, if one may use such a phrase. The protons are charged with positive electricity and the electrons with negative electricity.* The central portion of the atom is called its **nucleus**. It contains all the protons and about half of the electrons, and is of a complicated structure. The remaining electrons were at one time pictured as revolving about the nucleus, somewhat as the planets revolve about the sun. At the present time this idea has been pretty definitely discarded, but no satisfactory substitute has been found to replace it.

The hydrogen atom is the smallest and simplest of all and its mass is given as $1 \cdot 66 \times 10^{-24}$ gram. The mass of an electron is $\frac{1}{1840}$th that of a hydrogen atom, or $9 \cdot 0 \times 10^{-28}$ gram. The protons are much more massive than the electrons. but are much smaller, being $\frac{1}{2000}$th the size of the electrons.

A hydrogen atom has 1 electron outside the nucleus, an atom of helium has 2, an atom of lithium has 3, . . . of oxygen has 8, . . . of gold has 79, . . . of uranium has 92.

A hydrogen molecule is composed of 2 hydrogen atoms and its mass is $3 \cdot 2 \times 10^{-24}$ gram.

For centuries the old alchemists endeavoured to change a base metal such as lead into a noble one such as gold, but without success. In recent years, however, some such transmutation of one element into another has actually been

*Explained in Chapter LXIX.

accomplished on a minute scale, although it has not been done with any hope of getting rich thereby.

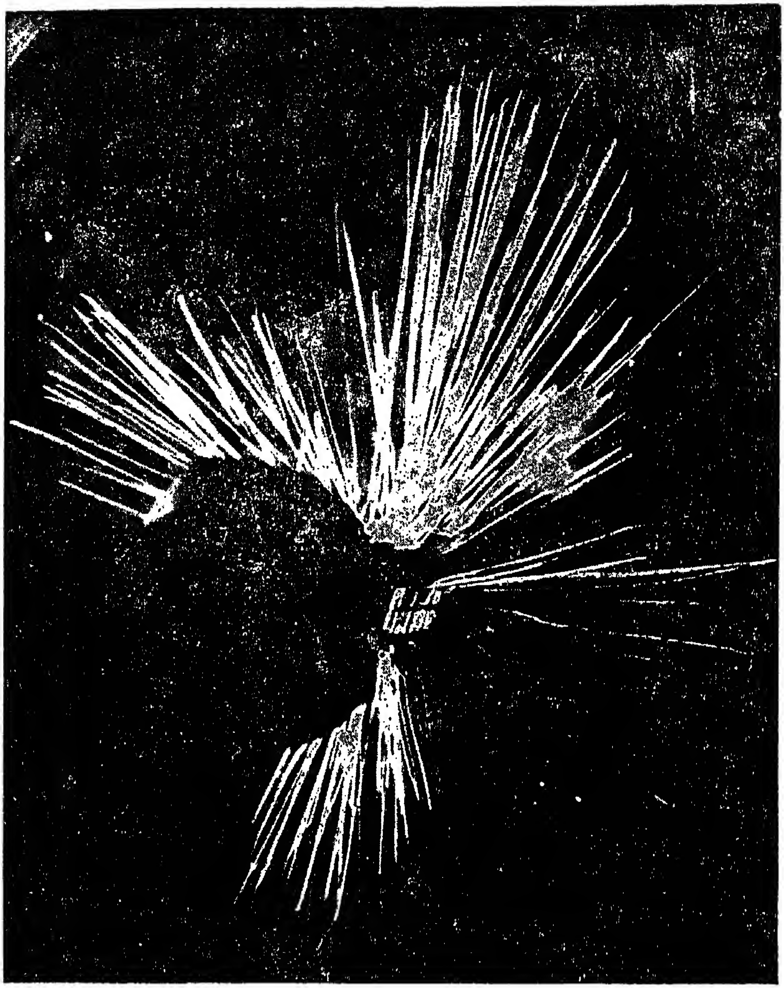
By electrical means it is possible to separate from a hydrogen atom its outer electron, and thus temporarily to set free its nucleus, which contains one proton; and then to project this proton against a target. In an experiment, the details of which cannot be explained here, the protons were projected with great speed against a thin film of lithium, each atom of which contains 3 protons in its nucleus and 3 electrons outside the nucleus. The atoms were broken up and there resulted particles containing 2 protons, which are the nuclei of helium atoms. They are also known as alpha particles. In the beginning there were hydrogen atoms, each with 1 proton and 1 electron, and lithium atoms, each with 3 protons and 3 electrons; and from these there came helium atoms, 2 of which had 2 protons and 2 electrons each or 4 protons and 4 electrons together, equivalent to 1 hydrogen atom and 1 lithium atom.

By suitable apparatus it is possible to photograph the paths of the resulting helium nuclei. They are shown in the plate facing this page.

165. Size of the Molecules. The problem of determining the size of the molecules of matter is one of great interest, but also one of extreme difficulty. It has been attacked in various ways, and the results obtained by processes entirely different from one another agree satisfactorily, which is good evidence that they are somewhere near the truth.

It is astonishing what small quantities of some substances can be detected by sight or smell or taste. One ten-millionth of a grain, or $3 \cdot 5 \times 10^{-9}$ gram, of magenta dye in solution can be detected by the eye; and 1×10^{-12} gram of mercaptan, a very strong-smelling substance, can be recognized. Each of these small quantities contains many atoms or molecules.

The number of molecules in 1 c.c. of gas at ordinary temperature and pressure is about $2 \cdot 77 \times 10^{19}$; and knowing the weight of 1 c.c. of any gas we can calculate the weight of 1 molecule of it. Thus 1 c.c. of hydrogen weighs $0 \cdot 00009$, or 9×10^{-5} gram, and hence 1 molecule of hydrogen weighs $3 \cdot 2 \times 10^{-24}$ gram, as stated in § 164. A single atom of lead



THE TRANSMUTATION OF MATTER

This photograph illustrates the transmutation of hydrogen and lithium into a different substance, helium. The white streaks are the paths of the helium nuclei or alpha particles as they came from the lithium seen just below the centre.

The original negative was taken by Mr. P. I. Dee in the Cavendish Laboratory, Cambridge University, England; and the photograph was sent for reproduction in this book by Lord Rutherford, the Director of the Laboratory.

"Thus Rutherford was the first man actually to transmute one element into another." (Loeb and Adams. The Development of Physical Thought, p. 564.)

Plate 19

would be contained in a cube having an edge of $3 \cdot 0 \times 10^{-8}$ cm. and it would weigh $3 \cdot 44 \times 10^{-22}$ gram.

These numbers are inconceivably small and the number of atoms in 1 c.c. is inconceivably great. Some illustrations of their magnitudes are given in the problems below which are easy to calculate.

Lord Kelvin many years ago calculated in several ways the size of molecules, and gave the following illustration: "Imagine a rain-drop, or a globe of glass as large as a pea, to be magnified up to the size of the earth, each constituent molecule being magnified in the same proportion. The magnified structure would be more coarse-grained than a heap of small shot, but probably less coarse-grained than a heap of cricket balls."

PROBLEMS

1. Suppose a cubic decimetre of lead to be sliced into square plates 10 cm. square, one atom thick (3×10^{-8} cm.), and the plates to be spread out just touching each other. What area would they cover?

2. An ordinary evacuated electric-light bulb has a volume of 114 c.c. Suppose a hole to be made in it and molecules of air to rush in at the rate of one million per second. How long will it take to fill the bulb so that the pressure within is equal to that without?

3. In a tumbler of water are approximately 10^{25} molecules, and all the water on the earth's surface contains about 5×10^{21} tumblerfuls. Suppose all the molecules in a tumbler of water to be labelled and the water then thrown into the ocean. If, after sufficient time has elapsed for the labelled molecules to be completely diffused through all the water, a tumbler of water is drawn from a tap, how many of the original molecules would there be in it?

REFERENCES FOR FURTHER INFORMATION

MENDENHALL, EVE AND KEYS: *College Physics*, Chapter 20.
LOEB AND ADAMS: *The Development of Physical Thought*, Chapter 6.
EDSER: *General Physics*, Chapters 9, 10, 16.
Also the references at the end of Chapter 86.

CHAPTER XXVIII

PHENOMENA OF SURFACE TENSION AND CAPILLARITY

166. Forces at the Surface of a Liquid. On slowly forcing water out of a medicine dropper we see it gradually gather at the end (Fig. 195), becoming more and more globular, until at last it breaks off and falls a sphere. When mercury falls on the floor, it breaks up into a thousand shining globules. Why do not these flatten out? If melted lead be poured through a sieve at the top of a tower, it forms into drops, which harden on the way down and finally appear as solid spheres of shot. Glass marbles are made by heating the end of a glass rod until a drop forms and falls away.

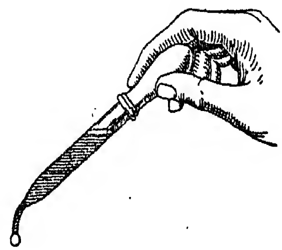


FIG. 195.—A drop of water assumes the globular form.

By mixing water and alcohol (about 60 water to 40 alcohol), it is possible to obtain a mixture of the same density as olive oil. If olive oil is introduced into the mixture by means of a pipette it immediately assumes a globular form (Fig. 196). In this case it is freed from the distorting action of gravity and rests anywhere it is put.

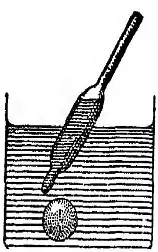


FIG. 196.—A sp of olive oil in a mixt of water and alcohol.

These actions are due to cohesion. A little consideration would lead us to expect the molecules at the surface to act in a manner somewhat different from those in the interior of a liquid. Let *a* be a molecule well within the liquid

(Fig. 197). The molecule is attracted on all sides by the molecules very close to it, within its sphere of action (which is extremely small, see § 157), and as the attraction is in all directions it will remain at rest. Next consider a molecule *b* which is just on the surface. In this case there will be no attraction on *b* from above, but the neighbouring molecules within the liquid will pull it downwards. Thus there are forces pulling the surface molecules into the liquid, bringing them all as close together as possible, so that the area of the surface will be as small as possible. It is for this reason that the water forms in spherical drops, since, for a given volume, the sphere has the smallest surface.

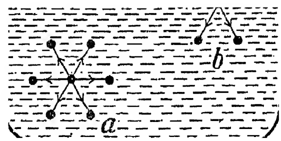


FIG. 197.—Behaviour of molecules within the liquid and at its surface.

The surface of a liquid behaves precisely as though a rubber membrane were stretched over it, and the phenomena exhibited are said to be due to **surface tension.**

167. Surface Tension in Soap Films. The surface tension of water is beautifully shown by soap bubbles and films. In these there is very little matter, and the force of gravity does not interfere with our experimenting. It is to be observed, too, that in the bubbles and films there is an outside and an inside surface, each under tension.

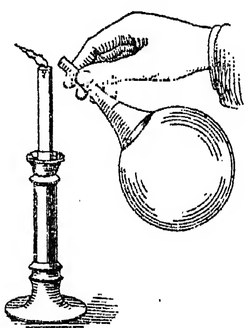


FIG. 198.—Soap-bubble blowing a candle flame aside.

In an inflated toy balloon the rubber is under tension. This is shown by pricking with a pin or untying the mouthpiece. At once the air is forced out and the balloon becomes flat. A similar effect is obtained with a soap bubble. Let it be blown on a funnel, and the small end be held to a candle flame (Fig. 198). The outrushing air blows

the flame aside, which shows that the bubble behaves like an elastic bag.

There is a difference, however, between the balloon and the bubble. The former will shrink only to a certain size; the latter first shrinks to a film across the mouth of the funnel and then runs up the funnel handle, ever trying to reach a smaller area.

Again, take a ring of wire about two inches in diameter with a handle on it (Fig. 199). To two points on the ring tie a fine thread with a loop in it. Dip the ring in a soap solution and obtain a film across it with the loop resting on the film. Now, with the end of a wire or with the point of a pencil puncture the film within the loop. Immediately the film which is left assumes as small a surface as it can, and the loop becomes a perfect circle, since by so doing the area of the film becomes as small as possible.

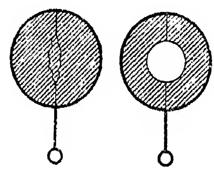


Fig. 199.—A loop of thread on a soap film.

168. Contact of Liquid and Solid. The surface of a liquid resting freely under gravity is horizontal, but where the liquid is in contact with a solid, the surface is usually curved. Water in contact with clean glass curves upward, mercury curves downward. Sometimes when the glass is dirty the curvature is absent.

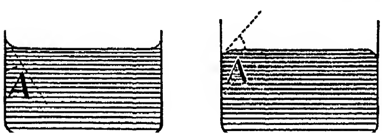


Fig. 200.—Water in a glass vessel curves up, mercury curves down.

These are called **capillary** phenomena, for a reason which will soon appear. The angle of contact A (Fig. 200) between the surfaces of the liquid and the solid is called the capillary angle. For perfectly pure water and clean glass the angle is zero, but with slight contamination, even such as is caused by exposure to air, the angle may become 25° or more. For pure mercury and clean glass the angle is about 148°, but slight contamination reduces this to 140° or less. For turpentine it is 17°, and for petroleum 26°.

169. Level of Liquids in Fine Tubes. If a small glass tube is held upright in water the liquid rises within the tube and, both inside and outside, the surface curves upward

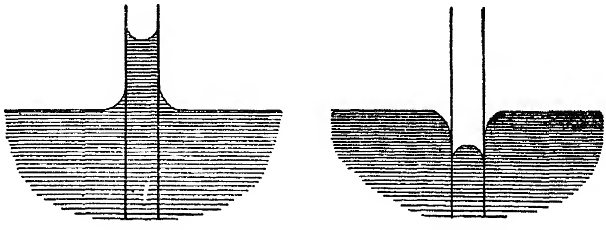


FIG. 201.—Level of liquid in a fine tube.

where it touches the glass (Fig. 201). This effect will be observed more easily if a little colouring matter (fluorescin, for example) is added to the water. If mercury is used instead of water, the liquid within the tube takes a lower level than that outside, and the surface at the glass curves

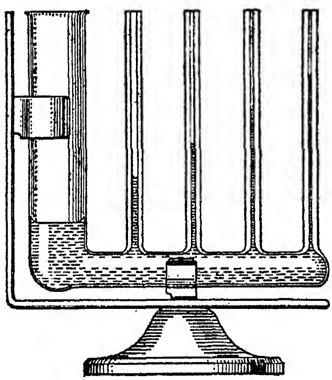


FIG. 202.—Showing the elevation of water in capillary tubes of different diameters.

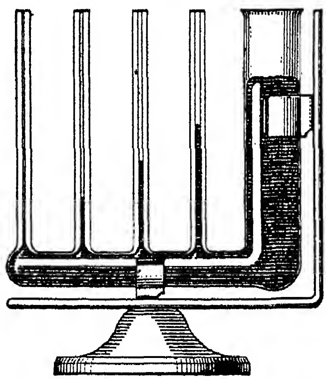


FIG. 203.—Showing the depression of mercury in capillary tubes of different diameters.

downward instead of upward. In these experiments the glass should be perfectly clean.

It is interesting to observe the effect with tubes of various sizes. Fig. 202 shows capillary* tubes having different in-

*Latin, *capillus*, a hair.

ternal diameters connected to a tube of large diameter. It will be seen that in each of the capillary tubes the level is above that of the water in the large tube and that **the finer the tube the higher is the level of the water.** With alcohol the liquid rises, though not so much, but with mercury the liquid is depressed. The behaviour of mercury is shown in Fig. 203. In this case **the finer the tube, the greater is the depression of the mercury.**

Experiment. Another convenient method of showing capillary action is illustrated in Fig. 204. Take two square pieces of window glass, and place them face to face, with an ordinary match or other small object to keep them a small distance apart along one edge while they meet together along the opposite edge. They may be held in this position by an elastic band. Then stand the plates in a dish of coloured water. The water at once creeps up between the plates, standing highest where the plates meet.

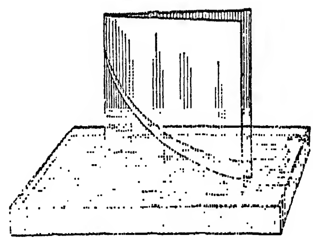


FIG. 204. — Water rises between the two plates of glass which touch along one edge.

When a glass rod is withdrawn from water, some water clings to it, and the liquid is said to wet the glass. If dipped in mercury, no mercury adheres to the glass. Mercury does not wet glass.

170. Explanation of Capillary Action. Capillary phenomena depend upon the relation between the cohesion of the liquid and the adhesion between the liquid and the tube.

In the case of capillary tubes the column of liquid which is above the general level of the liquid is held up by the adhesion of the glass tube for it. The total force exerted varies directly as the length of the line of contact of the liquid and the tube, which is the inner circumference of the tube; while the quantity of liquid in the elevated (or depressed) column is proportional to the *area* of the inner cross-section of the tube. If the diameter of the tube is doubled, the lifting force is doubled, and so the quantity of liquid lifted is doubled; but as the area is now *four* times as great the height of the column lifted is one-half as great.

Hence the elevation (or depression) varies inversely as the diameter of the tube.

The following are the chief laws of capillary action:

(1) **If a liquid wets a tube, it rises in it; if not, it falls in it.**

(2) **The rise or depression is inversely proportional to the diameter of the tube.**

171. Interesting Illustrations of Surface Tension and Capillarity. It is not easy to pour water from a tumbler into a bottle without spilling it, but by holding a glass rod as in Fig. 205 the water runs down into the bottle and none is lost. The glass rod may be inclined, but the elastic skin still holds the water to the rod.

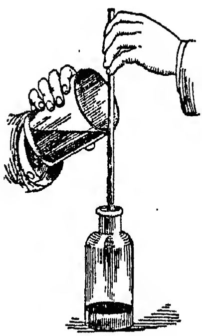


FIG. 205. — How to utilize surface tension in pouring a liquid.

Water may be led from the end of an eaves-trough into a barrel by means of a pole almost as well as by a metal tube.

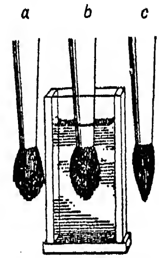


FIG. 206. — Surface tension holds the hairs of the brush together.

When a brush is dry, the hairs spread out as in Fig. 206*a*, but on wetting it they cling together (Fig. 206*c*). This is due to the surface film which contracts and draws the hairs together. That it is not due simply to being wet is seen from Fig. 206*b*, which shows the brush in the water but with the hairs spread out.

A brush made from badger hair will hold much water, or its capillary capacity is great. Hence superior shaving-brushes are made from this kind of hair, and they do not drip as inferior ones do.

A wire sieve is wet by water, but if it is covered with paraffin wax, the water will not cling to it. Make a dish out of copper gauze having about twenty wires to the inch; let its diameter be about six inches and height one inch. Bind it with wire to strengthen it. Dip it in melted paraffin wax, and while still hot knock it on the table so as to shake the wax out of the holes. An ordinary pin, will still pass through the holes, and there will be over 10,000 of them. On the bottom of the dish lay a small piece of paper and pour water on it. Fully half a tumblerful of water can be poured into the vessel and yet it will not leak. The water has a skin

over it, which will suffer considerable stretching before it breaks. Give the vessel a jolt, the skin breaks and the water at once runs out. A vessel constructed as described will also float on the surface of water.

Capillary action is seen in the rising of water in a cloth, or in a lump of sugar when touching the water; in the rising of oil in a lamp-wick and in the absorption of ink by blotting-paper. Water poured into the saucer under a flower-pot rises to the roots of the plant.

172. Small Bodies Resting on the Surface of Water.

FIG. 207.—Needle on the surface of water kept up by surface tension.

By careful manipulation a needle may be laid on the surface of still water (Fig. 207). In doing this a wire bent as in Fig. 208 may be used. The surface is made concave by laying the needle on it, and in the endeavour to contract and smooth out the hollow, sufficient force is exerted to support the needle, though its density is $7\frac{1}{2}$ times that of water. When once the water has wet the needle the water rises against the surface of the metal, and now the tendency of the surface of the liquid to flatten out will draw the needle downwards.

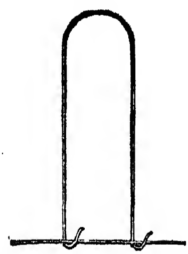


FIG. 208.—Stirrup for placing a needle on the surface of water.

If the needle is magnetized it will act, when floating, like a compass-needle, showing the north-and-south direction.

A safety razor blade may also be made to float, and in the case of both it and the needle, the experiment is more easily performed if they have a little oil on them.

FIG. 209.—Insect supported by the surface tension of the water.

Some insects run over the surface of water, frequently very rapidly (Fig. 209). These are held up in the same way as the needle, namely, by the skin on the surface, to rupture which requires some force.

173. Moisture in the Soil.

For plants to grow they must have moisture, the amount of water required for an ordinary farm crop being about 7 inches. The water which falls upon the soil is disposed of as follows (Fig. 210):

(*a*) By transpiration through the surface of the leaves of the living plants.

(*b*) By run-off over the surface of the ground.

(*c*) By percolation through the soil, some of the water escaping through drains.

(*d*) By evaporation at the surface of the ground.

The amount of water lost in each way depends on the nature of the soil and its condition.

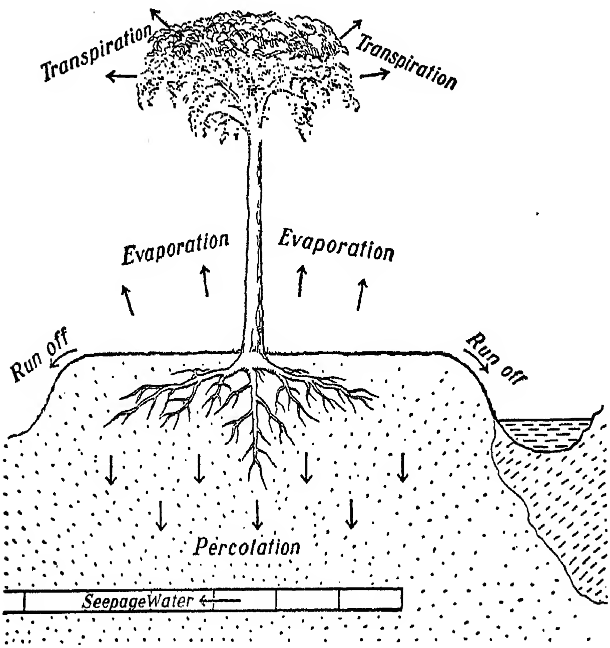


FIG. 210.—Ways by which water is lost from the soil.

To control run-off and percolation it is necessary (1) to have a loose, open granular soil, which allows free entrance of the water; and (2) to cultivate the soil so as to provide a high capillary capacity for water. Drainage, lime, humus, and good tillage assist in producing good granulation, which allows the soil to hold more water. This is one reason for fall and early spring plowing; it increases the capacity of the soil for moisture.

174. Evaporation at the Surface. The water present in the soil moves in all directions through the spaces between the particles of the soil by capillary action, just as water rises in a fine tube. In this way it

rises to the surface, and by some means it should be prevented from evaporating there. This may be done by a **mulch**, which may be of one of two kinds:

(1) Foreign materials, such as manure or leaves, is spread over the surface and effectively obstructs evaporation. In some European countries and in some localities in America stones actually have been drawn on the soil with beneficial results. This has been done especially in the culture of orchards and vineyards. In some places the removal of stones has made the soil harder.

(2) By cultivating from one to three inches at the surface. When this is done the water in this layer evaporates and it becomes air-dry. It is called a **soil mulch**. Capillary water which rises to this layer is checked in its upward motion and evaporation is prevented.

A single-layer of coarse paper such as is used by builders, laid between the rows of vegetables, effectively keeps down the weeds and prevents the moisture from escaping.

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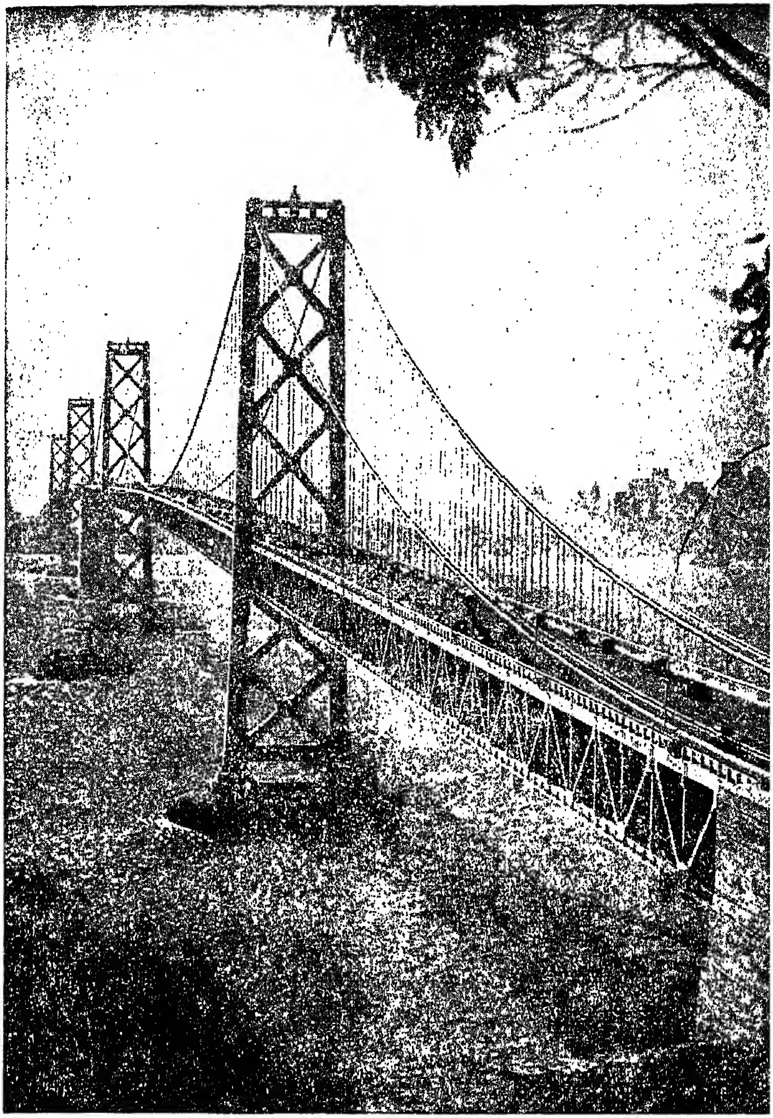
Merchant, Chant and Cline: *Mechanics*, Chapter 25.
N. E. Dorsey: *Scientific Papers of the Bureau of Standards*, Washington, D.C., No. 5[illegible] (Gives methods of measuring surface tension.)
Lyon, Fippin and Buckman: *Soils.*

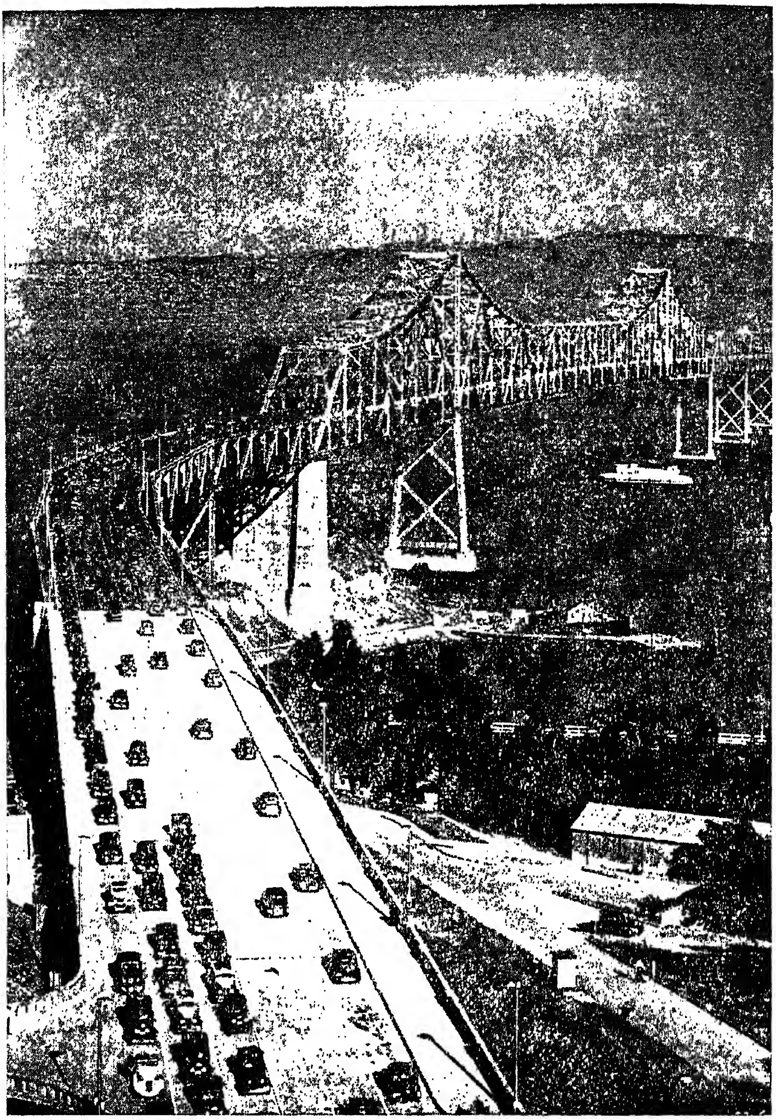


SAN FRANCISCO-OAKLAND BAY BRIDGE, SUSPENSION SPANS

The westerly portion consists of suspension spans, the easterly of cantilever spans. From the end of the western approach to the end of the eastern approach the distance is 8¼ miles. It is the longest in the world.

The above view shows the suspension spans at the San Francisco end. Highest tower, 519 ft. The two cables are 28¾ in. in diameter and each contains 17,464 wires. Total length of wires used, 70,800 miles.

(Photograph from California Toll Bridge Authority) **Plate 20**



THE SAN FRANCISCO-OAKLAND BAY BRIDGE, CANTILEVER SPANS

This view shows the cantilever spans of the easterly section, with the city of Oakland in the background.

The deepest pier is beneath the easterly end of the cantilever span and goes to rock at a depth of 242 ft. below the surface of the water. The bridge is about 200 ft. above high water. It was opened to traffic November 12, 1936. It required four years to build and cost $77,000,000.

(Photograph from California Toll Bridge Authority) **Plate 21**

PART V—HEAT

CHAPTER XXIX

SOURCES AND NATURE OF HEAT

175. Sources of Heat. The existence of plant and animal life depends upon its receipt of sufficient heat and the history of civilization is intimately connected with man's ability to utilize the heat obtainable in various ways. The chief sources of heat are:

e electric current.

Mechanical action

In every case where heat is produced it is simply transformed from some other form of energy.

176. Heat from the Sun. The sun is our greatest supply of heat, and even when we burn coal or wood to heat our homes we are indirectly making use of the heat energy of the sun which was responsible for the growth of the forests which gave us the fuel.

177. Heat from Chemical Action. The potential energy of chemical separation is one of our most common sources of heat. Combustible bodies, such as coal and wood, possess energy of this kind. When raised to the ignition point, they unite chemically with the oxygen of the air, and their union is accompanied by the development of heat. So far this has been the chief source of artificial heat used for cooking our food and warming our dwellings.

178. Heat from an Electric Current. An electric current possesses energy, and this, when the current is made to pass through a conductor which offers resistance to it, is transformed into heat. For example, if the terminals of a battery consisting of three or four dry cells joined in series are connected with a short piece of fine platinum or iron wire, it will be heated to a white heat. In electric lamps the carbon rods or the tungsten wires are heated to incandescence by an electric current. Electric heaters and electric cookers are merely coils of resistance wire heated by an electric current.

179. Heat from Mechanical Action. It is a matter of every day experience that when motion is checked by friction or collision, heat is developed in the bodies concerned. Thus if a button is rubbed vigorously on a board or even on a piece of cloth, it may be made too hot to be handled. A drill used in boring steel quickly becomes heated. A leaden bullet shot against an iron target may be melted by the impact. The aborigines obtained fire by rubbing two dry sticks together.

Heat is also developed by compression. If a piece of dry tinder* is placed in a tube closed at one end, and a closely-fitting piston is pushed quickly into the tube (Fig. 211), the tinder may be lighted by the heat developed by the compression of the air. The cylinders of air compressors (automobile and bicycle pumps for instance) become heated by the repeated compression of the air drawn into them. In the Diesel engine the fuel is ignited in the cylinder by the heat developed by compression.


Fig. 211.—A fire syringe.

Conversely, if a compressed gas is allowed to expand, its temperature falls. The steam which has done work by its expansion in driving forward the piston of a steam engine escapes from

*A pellet of cotton soaked in ether or carbon disulphide may be used instead.

the cylinder at a lower temperature than it had on entering the cylinder.

180. Nature of Heat. For centuries it was the general belief that the heating of a body was due to the entrance into it of a subtle weightless fluid called *caloric*. The first serious attack upon this theory was made by Count Rumford* in 1798. In some experiments a bar of steel was pushed with great force into a hole in a bronze cylinder which was made to rotate. He found that as long as the cylinder was rotated heat continued to be produced, and he concluded that, as there was no limit to the amount of heat produced, it could not be a form of matter but must be a kind of motion. In the years just after this Sir Humphry Davy and others made somewhat similar experiments, but not until about the middle of the century was the old theory finally overthrown. This was due to the experiments of Joule, of Manchester, who showed that the quantity of heat produced was proportional to the mechanical work done, twice as much heat requiring twice the amount of work, and so on, from which it was clear that **heat must be a form of energy.**

181. Motion of the Molecules. What becomes of the energy of a body when its motion is stopped by friction or collision? It is changed into motion of the molecules of the body, and the more vigorous the motion of the molecules the greater is the heat energy possessed by the body. Consider what happens when a body, a piece of lead for instance, is heated. The molecules within it vibrate back and forth, striking their neighbours harder and harder as the temperature rises. This shaking about of the molecules becomes so vigorous that the bonds between them are weakened, the lead softens and then melts. After this the molecules move freely about in the liquid, and as the heat is still further

*Benjamin Thompson was born at Woburn (near Boston, Mass.) in 1753. In 1775 he went to England and in 1783 to Austria. He was created Count Rumford by the Elector of Bavaria. While engaged in boring cannon at Munich he made his experiments on heat. He died in France in 1814.

applied they fly off and the liquid evaporates or turns into vapour. We are familiar with ice turning into water and then into vapour, but many other substances behave in the same way.

182. Heat from Radiant Energy. The sun, as has been remarked, is our most important source of heat, but its heat, defined as the energy of molecular motion, does not come unchanged from sun to earth, as one might suppose. The atmospheres of the sun and the earth extend only a few hundred miles from these bodies, while they are 93,000,000 miles apart. It is certain that in most of the space between them there is no matter, composed of molecules, as we understand it. The direct transference of molecular motion from the sun to the earth is, therefore, impossible. To account for the transmission of energy, the physicist assumes the existence of a medium called the **ether,** which he conceives to pervade all space, penetrating between the molecules as well as reaching from star to star.

It is supposed that the vibrating molecules of a hot body set up disturbances in the ether, and that these are transmitted in all directions by a species of wave-motion. When these ether waves fall upon matter, they tend to accelerate the motion of its molecules and so to heat it. Thus the heat of the sun is first changed into **radiant energy,** or the energy of ether vibration, and the ether waves which fall upon the earth are transformed into heat. The subject is further discussed in § 268.

QUESTIONS

1. Give examples of heat produced by:
(*a*) Chemical action, (*b*) the electric current, (*c*) mechanical action.

2. What substances are commonly used to obtain heat at the expense of chemical energy?

3. Most of our electrical energy is obtained from generators driven by water-power. Show that the heat energy of the sun is the ultimate source of the water-power.

4. What transformations of energy take place in a motor car:

(*a*) When the spark occurs at the spark-plug, (*b*) when the mixture of gasoline vapour and air explodes, (*c*) when the engine drives the car, (*d*) when the starting-motor turns the engine, (*e*) when the brakes are set to stop the moving car?

5. What experimental evidence led Rumford to believe that heat is not matter but energy?

6. Outline the molecular theory of heat.

REFERENCES FOR FURTHER INFORMATION

EDSER, *Heat for Advanced Students*, Chapter 12.
PRESTON, *Theory of Heat*, Chapter 1.

CHAPTER XXX

EXPANSION THROUGH HEAT

183. Expansion of Solids by Heat. There are numerous examples of the expansion of bodies through heat, and many simple experiments have been devised to illustrate it.

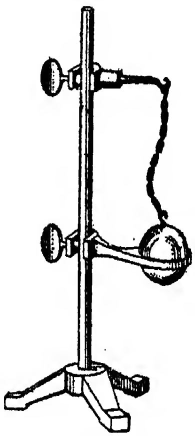


Fig. 212.—Expansion of ball by heat.

1. Take a brass ball (Fig. 212) which can just pass through a ring when cold, and then heat it. It will be found to be too large to go through.

2. In the apparatus shown in Fig. 213,

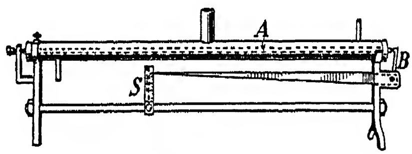


Fig. 213.—Expansion of rod by heat.

a metal rod A is fixed at one end while the other presses against the short arm of a bent lever B. If the rod is heated its elongation will be shown by the movement of the end of the long arm over a scale S.

3. Fig. 214 shows a compound bar constructed by riveting together strips of copper and iron. When it is heated uniformly it bends into a curved form with the copper on the convex side, because the copper expands more than the iron. If placed in a cold bath, it curves in the opposite direction.

Fig. 214.— pound bar by of its parts.

These experiments illustrate a very general law. **Solids (with very few, if any, exceptions) expand when heated and**

contract when cooled, but different solids have different rates of

184. Expansion of Liquids and Gases by Heat. Liquids also expand when heated. The amount of expansion varies with the liquid, but, on the whole, it is much greater than that of solids. Let us fill a flask (Fig. 215) with a liquid and then insert a stopper through which passes a glass tube, making sure that the liquid is visible in the tube. When the flask is heated the liquid is seen to rise in the tube. When the flask cools again the liquid sinks.

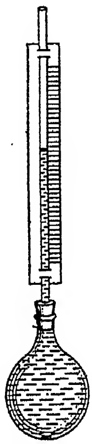


FIG. 215. — Expansions of liquids by heat.

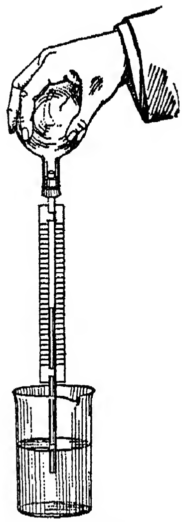


FIG. 216.—Expansion of a gas by heat.

The same apparatus may be used to illustrate the expansion of gases. When the flask and tube are filled with air only, insert the open end of the tube into water (Fig. 216), and heat the flask. A portion of the air is seen to bubble out and through the water. If the flask is cooled, water is forced by the pressure of the outer air into the tube to take up the space left by the air as it contracts.

Unlike solids and liquids, all gases have, at the ordinary pressure of the air, approximately the same rates of expansion.

185. Applications of Expansion—Compensated Pendulums. A clock is regulated by a pendulum whose rate of vibration depends on its length. The longer the pendulum, the slower the beat; and the shorter, the faster. Changes in temperature will, therefore, cause irregularities in the running of the clock, unless some provision is made for keeping the pendulum

constant in length through varying changes in temperature. Several forms of compensation are in use. The Graham pendulum (Fig. 217) is provided with a bob consisting of a jar of mercury. Expansion in the rod lowers the centre of gravity of the bob, while expansion in the mercury raises it. The quantity of mercury is so adjusted as to keep the centre of gravity* always at the same level.

Fig. 217.—Graham pendulum, invented in 1722.

In the Harrison, or gridiron, pendulum (Fig. 218) the bob hangs from a framework of brass and steel rods, so connected that an increase in length of the steel rods (dark in the figure), tends to lower the bob, while an increase in the length of the brass ones tends to raise it. The lengths of the two sets are adjusted to keep the resultant length of the pendulum constant.

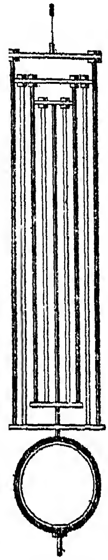


Fig. 218.— i npendulum, r ented in 1726

In the best modern clocks the pendulum consists of a rod of *invar*, an alloy of nickel 63·8 per cent. and steel 36·2 per cent., the expansion of which is small, and a bob of brass, lead or other metal (Fig. 219.)

Fig modern p lum, with rod and a bob.

186. Chronometer Balance-wheel. A watch is regulated by a balance-wheel, controlled by a hairspring (Fig. 220). An

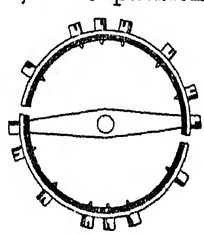


Fig. 220.—Balance-wheel of watch.

*Strictly speaking, it is a point called the *centre of oscillation*, (which nearly coincides with the centre of gravity) whose distance from the point of suspension should be kept constant.

elevation in temperature tends to increase the diameter of the wheel and to decrease the elasticity of the spring. Both effects would cause the watch to lose time. To counteract the retarding effects, the rim of the balance-wheel in chronometers and high-grade watches is constructed of two metals and mounted in sections, as shown in Fig. 220. The outer metal is the more expansible, and the effect of its expansion is to turn the free ends of the rim inwards, and thus to lessen the effective diameter of the wheel.

187. Thermostats. The curling up of a compound bar when heated

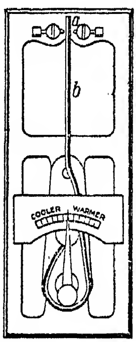


Fig. 221.—An electric thermostat.

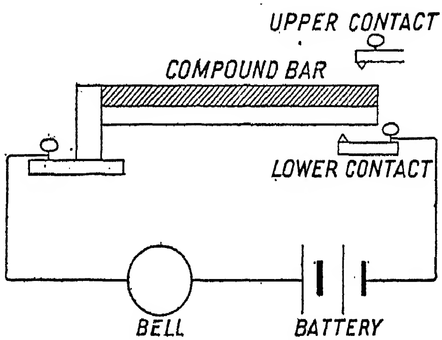


Fig. 222.—A simple compound bar thermostat arranged to ring a bell.

is applied in the construction of thermostats, which are used mainly for controlling the temperature of buildings heated by hot-air furnaces or boilers. The thermostat is so constructed that, when the temperature rises to a certain degree, it sets free a current of electricity or a supply of compressed air, which closes the dampers or the steam valves; and when the temperature falls, the heat is turned on again. In Fig. 221 is shown an electric thermostat. The essential part is the compound bar *b*. When bent by the heat, it closes an electric circuit at *a*. In the pneumatic thermostat the bending of the bar shuts off the escape of compressed air and causes it to open a valve which allows a large supply of compressed air to have access to the regulators in the furnace-room.

Experiment. Connect a simple compound bar thermostat in series with two dry cells and an electric bell as shown in Fig. 222. If the more expansible metal is on the top of the bar, what should happen when the bar is heated gently? Verify your prediction. What practical use could

be made of such a circuit? What change would you make in the connections so that the bell would ring if the bar were cooled?

188. Metallic Thermometer. The curling up of a compound bar when heated is also applied in the construction of a metallic thermometer. In Fig. 223 is a thermometer such as is used to show the temperature of an oven. The diagram shows a rear view of the thermometer. It consists of a long compound bar wound in a spiral *S*, with the metal having the greater expansion on the outside. The bar is fastened rigidly at one end *A*. The motion of the other end *B* when the spiral is heated is transmitted to a pointer *P* by means of a lever which moves about an axis *O*. Cogs on one end of the lever engage with those in a wheel which rotates about an axis *M*. At the end of this axis is attached the pointer *P* which moves over a scale indicating the temperature in degrees Fahrenheit. Part of the metal plate is cut away to show the pointer. The scale and pointer are shown as they would appear if the face of the thermometer were transparent.

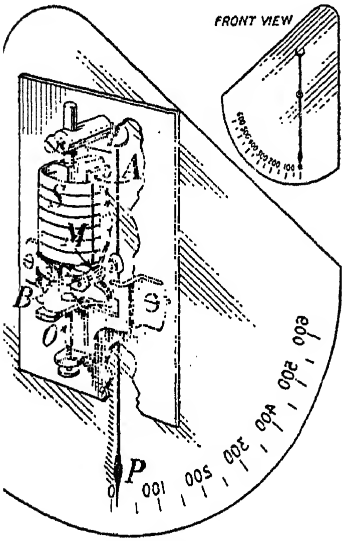


FIG. 223.—A metallic thermometer for high temperatures such as in baking.

QUESTIONS

1. A glass stopper stuck in the neck of a bottle may sometimes be loosened by subjecting the neck to friction by a string. Explain.

2. Boiler plates are put together with red-hot rivets. What is the reason for this?

3. A tire for a wagon wheel or one for a locomotive driving-wheel is heated before adjusting to the wheel. Why?

4. Why are the rails of a railroad track laid with the ends not quite touching?

5. Why does change in the temperature of a room affect the tone of a piano?

6. Glass vessels are liable to break when hot water is poured into them. Give the reason.

7. In repairing a cannon a hole was drilled into it, and a plug was made just too large to go into the hole. The plug was then held in liquid air for some time, and then it went into the hole and could never be withdrawn. Explain.

8. In constructing large guns the barrel or inner tube is surrounded by several layers, each being heated and then slipped over the layer within it. Why? When the barrel is worn out by firing, the whole gun is heated, a jet of water is sent into the barrel and the inner tube is then driven out. Explain why this is possible. (See *Encyclopedia Britannica*, Article "Ordnance.")

9. How would you provide for expansion in steam pipes?

10. In building a bridge one end of a steel span is held fixed and the other placed on rollers, as in Fig. 224. Explain why.

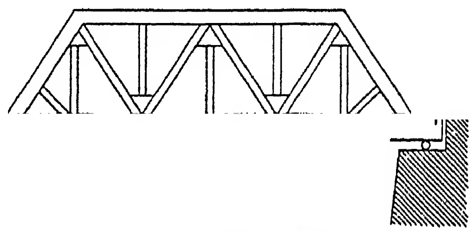


FIG. 224.—Allowing for expansion.

11. A concrete road is laid in sections separated by narrow spaces filled with pitch. What happens to concrete and to pitch with a rise of temperature?

12. A steel tape and a linen tape were equal in length when compared in a warm room, but different results were obtained when they were used to measure the length of a field on a cold day. Explain.

13. The vertical shaft of one of the great generators at the Queenston Hydro-electric plant (see Figs. 92, 658, and Plates facing pages 92, 576) was damaged early in 1937 and had to be removed for repairs. The shaft is 32 ft. long, 32 in. in diameter, weighs 40 tons, and there is an 8-in. hole along its axis. The entire rotor, weighing 270 tons, was supported by a powerful crane and slightly warmed. Into a near-by tank containing 350 gals of alcohol 6 tons of "dry ice" was put and the temperature of the liquid fell to about $-100°$ F. This liquid was circulated through the 8-in. bore in the shaft which after some minutes slipped out. Explain why.

REFERENCES FOR FURTHER INFORMATION

A. E. E. McKenzie, *Heat*, Chapter 2.
Edser, *Heat for Advanced Students*, Chapters 3, 4.

CHAPTER XXXI

TEMPERATURE

189. Nature of Temperature. In our everyday experiences, we constantly refer to bodies as hot or cold, and use the word temperature in speaking of their conditions of hotness or coldness. Now, when is a body hot, and when cold, and what is meant by temperature?

When the blacksmith throws a piece of red-hot iron into a tub of cold water to cool it, the iron evidently loses heat, while the water gains it. When two bodies, like the iron and the water, are in such a condition that one grows warmer and the other colder when they are brought in contact, they are said to be at different temperatures. The body which gains heat is said to be at a lower temperature than the one which loses it. If neither grows warmer when the bodies are brought together, they are said to be at the same temperature. Temperature, therefore, may be defined as **the condition of a body considered with reference to its power of receiving heat from, or communicating heat to, another body.**

190. Temperature and Quantity of Heat. A pint of water taken from a tank is at the same temperature as a gallon taken from the same source. They will also be at the same temperature when both are brought to the boiling-point, but if they are heated by the same gas flame, it will take much longer to bring the gallon up to the boiling-point than to raise the pint to the same temperature. The change in temperature is the same in each, but the **quantity of heat** absorbed is different. A large radiator, filled with hot water may, in cooling, supply sufficient heat to warm up a room, but a small pitcher of water loses its heat with no apparent effect on its surroundings. **The quantity of heat possessed by a body evidently depends on its mass as well as its temperature.**

191. Determination of Temperature. Up to the time of Galileo, no instrumental means of determining temperature had been devised. Differences in the temperature of bodies were estimated by comparing the sensations resulting from contact with them. But simple experiments will show that our temperature sense cannot be relied upon to determine temperature with any degree of accuracy. Take three vessels, one containing water as hot as can be borne by the hand, one containing ice-cold water, and one with water at the temperature of the room. Hold a finger of one hand in the cold water and a finger of the other in the hot water for one or two minutes, and immediately insert both fingers in the third vessel. To one finger the water will appear to be hot, and to the other, cold. The experiment shows that our estimation of temperature depends, to a certain extent, on the temperature of the part of our body used in making the determination. Our ordinary experiences confirm this conclusion. If we pass from a cold room into one moderately heated, it appears warm, while the same room appears cold when we enter it from one that is overheated.

Again, our estimation of the temperature of an object depends on the nature of the object as well as upon its temperature. It is a well-known fact that on a very cold day a piece of iron exposed to frost feels much colder than a piece of wood, although both may be at the same temperature.

192. Galileo's Thermometer. So far as known, Galileo was the first to construct a thermometer. He conceived that since changes in the temperature of a body are accompanied by changes in its volume, these latter changes might be made to measure, indirectly, temperature. He selected air as the material to be employed as a thermometric substance.

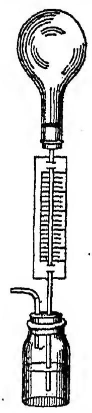


FIG. 225.—Galileo's air thermometer.

His thermometer consisted simply of a glass

bulb with a long, slender, glass stem made to dip into water, as shown in Fig. 225. Warming the bulb caused a few bubbles of air to escape out of the stem, and when it cooled the water rose part way up the stem. Any rise in temperature was then indicated by a fall of the water in the tube, and a fall in temperature by a rise of the water. Such a thermometer is imperfect, as the height of the column of liquid is affected by changes in the pressure of the outside air, as well as by changes in the temperature of the air within the bulb. According to Viviani, one of Galileo's pupils, 1593 was the date of the invention of the instrument.

193. Improvements in the Thermometer. About forty years later, Jean Rey, a French physician, improved the instrument by using water instead of air as the expansible substance. The bulb and a part of the stem were filled with water. Further improvements were made by the Florentine academicians (1657-1667), who made use of alcohol instead of water, sealed the tube, and attached a graduated scale. The first mercury thermometer was constructed by the astronomer Ismaël Boulliau, in 1659.

194. Construction of a Mercury Thermometer. Alcohol is still used to measure very low temperatures, but mercury is found in most thermometers in common use. This liquid has been selected for a variety of reasons. Among others the following may be noted:

(1) It can be used to measure a fairly wide range of temperatures, because it freezes at a low temperature and boils at a comparatively high temperature.

(2) At any definite temperature it has a constant volume.

(3) Slight changes in temperature are readily noted, as it expands rapidly with a rise in temperature.

(4) It does not wet the tube in which it is inclosed.

(5) It is opaque and easily seen.

To construct a thermometer a piece of thick-walled glass tube with a uniform capillary bore is chosen and a bulb of the proper size is blown on one end. Also a cup or funnel is formed on the other end. The bulb and tube have then to be filled with mercury. First, clean mercury is poured into the funnel, but it does not run down the fine tube. Then the bulb is heated, driving out some of the air, and on allowing all to cool some mercury goes down the tube into the bulb. By repeating the process of heating and cooling several times the bulb and tube are filled with mercury entirely free of air. The bulb and tube are then immersed in a bath at a temperature rather higher than the highest at which the thermometer will be used. Some of the mercury expands into the funnel and is removed, and then as the remainder cools and contracts the end of the tube is sealed off.

QUESTIONS

1. Why is a tube with a small bore necessary and what is the function of the bulb?

2. When, in constructing the thermometer, the bulb was heated and then cooled why did the mercury go down the tube?

195. Determination of the Fixed Points. Since we can describe a particular temperature only by stating how much it is above or below some temperature assumed as a standard, it is necessary to fix upon standards of temperature and also units of difference of temperature. This is most conveniently done by selecting two fixed points for a thermometric scale. The standards in almost universal use are the "freezing-point" and the "boiling-point" of water.

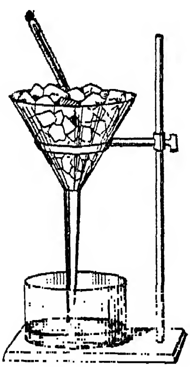


Fig. 226.—Determination of the freezing-point.

To determine the freezing-point, the thermometer is surrounded with moist pulverized ice (Fig. 226), and the point at which the mercury stands when it becomes stationary is marked on the stem.

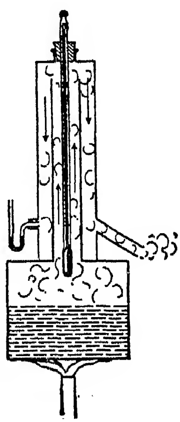


Fig. 227.—Determination of boiling-point.

The boiling-point is determined by exposing the bulb and stem to steam rising from pure water boiling under a pressure of 76 cm. of mercury (Fig. 227). As before, the height of the mercury is marked on the stem.

196. Graduation of the Thermometer. Having marked the freezing-point and the boiling-point, the next step is to graduate the thermometer. Two scales are in common use —the **Centigrade** scale and the **Fahrenheit** scale.

The Centigrade scale, first proposed by Celsius, a Swedish scientist, in 1740, and subsequently modified by his colleague Märten Strömer, is now universally employed in scientific work. The space between the freezing-point and the boiling-point is divided into one hundred equal divisions, or degrees, and the zero of the scale is placed at the graduations being extended both above and below the zero mark.*

The Fahrenheit scale is in common use among English-speaking people for meteorological observations and for household purposes. It was proposed by Gabriel Daniel Fahrenheit (1686-1736), a German instrument maker. The space between freezing-point and the boiling-point is divided one hundred and eighty equal divisions, each called a degree, and the zero is placed thirty-two divisions below the freezing-point, therefore, reads 32° and the boiling-point 212° (B and A, Fig. 228). This zero was chosen, it is said, because Fahrenheit believed this temperature, obtained from a mixture of melting ice and ammonium chloride or sea-salt, to be the lowest attainable.

Fig. 228.—Thermometer scales.

197. Comparison of Thermometer Scales. If we are given a reading on one scale it is easy to convert it into the equiva-

*Celsius at first marked the boiling-point zero and the freezing-point 100. It is said that the great botanist Linnaeus prompted Celsius and Strömer to invert the scale.

lent reading on the other, as will appear from the following simple problems.

Examples. (1) Suppose the temperature of the room is 68° on the Fahrenheit scale; how would it be expressed on the Centigrade scale?

The temperature 68 is 68 − 32, or 36, degrees above the freezing point.

But 180 Fahr. degrees = 100 Cent. degrees,

or 9 Fahr. degrees = 5 Cent. degrees,

and 36 Fahr. degrees = 20 Cent. degrees.

Hence the Centigrade reading is 20 degrees above the freezing point and is therefore 20° C. Thus 68° F. is equivalent to 20° C. (see Fig. 229).

(2) Convert − 20° C. to the equivalent reading on the Fahrenheit scale. In working such problems is it well to represent the conditions on a diagram (Fig. 229).

The reading − 20° C. means 20 Cent. degrees below freezing point.

Then 100 Cent. degrees = 180 Fahr. degrees,

1 Cent. degree = $\frac{9}{5}$ Fahr. degree,

20 Cent. degree = 36 Fahr. degrees.

FIG. 229.—Comparing C. and F. readings.

Now 36 Fahr. degrees below freezing point brings us to the reading (32 − 36)° F. = − 4° F.

The general relation between corresponding readings on the two thermometers may be obtained in the following way. Let a certain temperature be represented by $F°$ on the Fahrenheit and $C°$ on the Centigrade scale. Then this temperature is $F - 32$ Fahrenheit degrees above the freezing-point, and it is also C Centigrade degrees above the freezing-point. Hence

$(F - 32)$ Fahr. degrees correspond to C Cent. degrees.

But 9 Fahr. degrees correspond to 5 Cent. degrees,

Therefore $\frac{5}{9}(F - 32) = C$.

198. Maximum and Minimum Thermometers. A maximum thermometer is one which records the highest temperature reached during a certain time. One form is shown in Fig. 230. It is a mercury ther-

mometer with a constriction fixed in the tube just above the bulb (*c*, Fig. 230). As the temperature rises, the mercury expands and goes past the constriction; but when it contracts, the thread breaks at the constriction, that portion below it contracting into the bulb, while the mercury in the tube remains in the position it had when the temperature was highest. By gently tapping or shaking the thermometer, the mercury can be forced past the constriction, ready for use again.

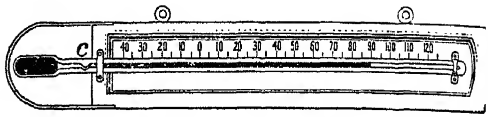


FIG. 230.—A maximum thermometer (as used in the Meteorological Service).

The clinical thermometer, with which the physician takes the temperature of the body, is constructed in this way.

In another kind of maximum thermometer a small piece of iron is inserted in the stem above the mercury (Fig. 231), and is pushed forward as the mercury expands. When the mercury contracts, the iron is left behind, and thus indicates the highest point reached by the mercury.

FIG. 231.—The iron index is pushed forward by the mercury.

In the minimum thermometer, which registers the lowest temperature reached, alcohol is used. Within the alcohol a small glass index is placed (Fig. 232). As the alcohol contracts, on account of its surface tension (§ 166), it drags the index back, but when it expands, it flows past the index, which is thus left stationary and shows the lowest temperature reached. Tilting the thermometer causes the index to slip down to the surface of the alcohol column, ready for use again.

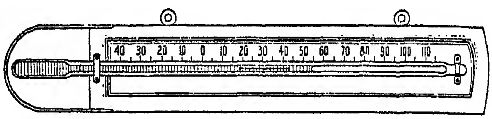


FIG. 232.—A minimum thermometer (as used in the Meteorological Service). It is hung in a horizontal position.

QUESTIONS AND PROBLEMS

1. Explain what you mean by the terms *hot* and *cold.*

2. Distinguish between *temperature* and *quantity of heat.*

3. Why is mercury used in most thermometers?

4. When the bulb of a thermometer is placed in hot water, the mercury drops perceptibly at first and then rises. Explain.

5. Why are air thermometers not in common use?

6. To how many Fahrenheit degrees are the following Centigrade degrees equivalent: 5, 15, 35, 65?

7. To how many Centigrade degrees are the following Fahrenheit degrees equivalent: 9, 27, 36, 95?

8. How many Fahrenheit degrees above freezing-point is 25° C.?

9. How many Centigrade degrees above freezing-point is 59° F.?

10. Convert the following readings on the Centigrade scale to Fahrenheit readings: 10°, 20°, 32°, 75°, – 20°, – 40°, and – 273°.

11. Convert the following readings on the Fahrenheit scale to Centigrade readings: 59°, 41°, 32°, 14°, 0°, – 22°.

12. Find in Centigrade degrees the difference between 30° C. and 16° F.

REFERENCES FOR FURTHER INFORMATION

GLAZEBROOK, *Heat*, Chapter 3.
NIGHTINGALE: *Heat, Light and Sound.*

CHAPTER XXXII

RATE OF EXPANSION: SOLIDS AND LIQUIDS

199. Coefficient of Expansion of Solids. It is frequently necessary to calculate with accuracy the changes in dimensions which bodies undergo through changes in temperature, as for example, when allowances are to be made for expansion and contraction in materials used for structural purposes or when different metals are used in building a machine. It is necessary to know in these calculations the **rate** at which the various materials employed expand.

The rate of expansion in length of solids is known as the coefficient of linear expansion, and the rate of expansion in volume, as the coefficient of cubical expansion.

The Coefficient of Linear Expansion may be defined as the increase in length experienced by a rod of unit length when its temperature is raised one degree.

200. Coefficient of Linear Expansion. We may find the coefficient of linear expansion of a metal by using the simple apparatus shown in Fig. 233. *A* is a horizontal brass jacket tube fitted at the ends with corks through which passes the metal rod *B*, whose coefficient we wish to find. Two small side tubes *C* and *D* are attached to *A* near the ends and steam from a florence flask or other generator enters by *C* and escapes at *D*. A thermometer *T* is fitted into a third tube at the middle.

The jacket is supported by two uprights *E* and *F* which are fastened to the base of the apparatus. An adjusting screw *G* touches one end of the rod and the other end makes contact with the shorter arm of the bent lever *HKL* which is pivoted at *K*. The end *L* of the long arm of the lever moves over a scale *S*.

Before assembling the apparatus measure the length of the rod at room temperature with a metre stick. Then place it in the jacket, taking care that both G and H are in contact with the rod, and note the temperature and also the position of L on the scale.

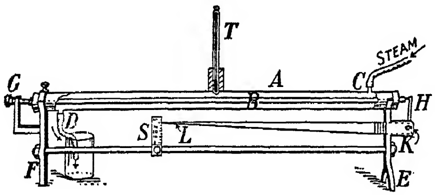


Fig. 233.—Simple apparatus for finding the coefficient of linear expansion of a metal rod.

Next pass steam through the jacket until the thermometer is steady and no further motion of L takes place. Then carefully take the new temperature and scale reading, making sure again that the screw and the lever are both in contact with the rod. Measure the lengths of the two arms of the lever and compute the coefficient as in the following example:

Length of brass rod at 20° C. . . . . 60 cm.

Movement of lever over scale . . . . 0·92 cm.

Ratio of arms of lever 1:10

Actual elongation of rod . . . . 0·092 cm.

Final temperature of rod . . . . 100° C.

60 cm. brass heated through 80 C. deg. lengthened 0·092 cm.

1 cm. brass heated through 1 C. deg. lengthened 0·0000188 cm.

Hence coefficient of expansion = 0·0000188

A general expression for the coefficient of linear expansion is

$$l_1 (l_2 - t_1)$$

where l_1 is the length of the rod at the temperature t_1 and l_2 the length at the temperature t_2.

More accurate results may be obtained if the elongation of the rod is measured by means of a good micrometer attached to the apparatus in place of the lever arrangement shown in the figure. This improvement would, however, make the apparatus more expensive.

201. Table of Coefficients. The following table gives the coefficients of linear expansion of some common

The coefficient of cubical expansion of a solid is usually determined by a calculation from the linear coefficient. It is approximately three times the coefficient of linear expansion.

COEFFICIENTS OF LINEAR EXPANSION FOR 1 CENTIGRADE DEGREE

Substance	Coefficient	Substance	Coefficient
Aluminium	0·0000231	Nickel	0·0000128
Brass	0·0000190	Platinum	0·0000090
Copper	0·0000168	Pyrex glass	0·0000032
Glass	0·0000090	Silver	0·0000192
Gold	0·0000144	Steel	0·0000132
Invar	0·0000009	Tin	0·0000223
Iron wire	0·0000144	Concrete	0·0000144

It will be noted that invar, which is an alloy of nickel and steel (see § 185) has an expansion only one-tenth that of platinum (which is small), that the expansion of pyrex is less than half that of ordinary glass, and that the expansion of concrete is the same as that of iron wire.

QUESTIONS AND PROBLEMS

1. From the table above what kind of wire would you choose as being most suitable to seal through glass for electrical purposes? Give reasons. Which for pyrex glass? Why may iron wires or rods be used to reinforce concrete? Could copper wires?

2. Why are pyrex test tubes and beakers better than those made of ordinary glass? Give other uses of pyrex.

3. The coefficient of linear expansion of steel for 1 Cent. deg. is 0·0000132; what is it for 1 Fahr. deg.?

4. A steel wire is 4 feet long at a temperature of 16° C. What is its length at 20° C.?

5. A brass scale is exactly one metre long at 0° C. What is its length at 18° C.?

6. The main span of the great steel bridge at Quebec is 1,800 ft. long. What change in its length would occur between − 25° F. and 100° F.?

7. Show that the coefficient of area expansion of a metal is approximately twice and the coefficient of volume expansion approximately

three times the coefficient of linear expansion. (If the coefficient of linear expansion $= a$, then a piece of metal 1 cm. square will have an area of $(1 + a)^2$ sq. cm. when the temperature rises 1 Centigrade degree. The increase is $(1 + a)^2 - 1 = 2a + a^2$ sq. cm. This is nearly $2a$ sq. cm.)

8. A pane of glass is 12 inches long and 10 inches wide at a temperature of 5° C. What is the area of its surface at 15° C.?

202. Coefficient of Expansion of Liquids. Like solids, different liquids expand at different rates. Many liquids also are very irregular in their expansion, having different coefficients at different temperatures.

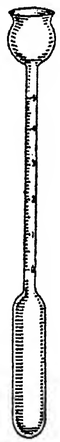


FIG. 234. — Determination of the coefficient of expansion of a liquid.

The coefficient of volume expansion of a liquid may be determined with a fair degree of accuracy by a modification of the experiment described in § 184. A suitable apparatus is shown in Fig. 234. It is called a dilatometer and consists of a bulb with a measured volume (usually 10 c.c.) and a finely-graduated capillary tube. The bulb is filled with the liquid to be tested and is heated in a bath. At various temperatures the level of the liquid in the tube is observed and the coefficient of the volume expansion can be calculated. For greater accuracy corrections should be made for changes in the capacities of the bulb and tube through changes in temperature.

Example. A dilatometer containing alcohol shows a reading of 10·014 c.c. at 20° C. and 10·375 c.c. at 50° C. Find the coefficient of expansion of alcohol between these temperatures.

Neglecting the expansion of glass,

10·014 c.c. alcohol heated through 30 C. deg. expanded ·361 c.c.

1 c.c. alcohol heated through 1 C. deg. expanded ·00120 c.c.

Hence coefficient of apparent expansion of alcohol = ·00120.

To this should be added the coefficient of volume expansion of the glass which we will assume to be ·00001 (pyrex).

Hence, coefficient of expansion of alcohol = ·00121.

203. Peculiar Expansion of Water; its Maximum Density. If the bulb and tube shown in Fig. 234 is filled with water

at the temperature of the room—say 20° C.—and the bulb placed in a cooling bath, the water will regularly contract in volume until its temperature falls to 4° C., and then it will expand until it comes to the freezing-point. Conversely, if water at 0° C. is heated, it will contract in volume until it reaches 4° C., and then it will expand.* Hence, a given mass of water has minimum volume and maximum density when it is 4° C.

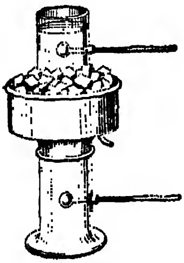


FIG. 235.—Hope's apparatus.

Experiment. The apparatus devised by Hope shows in a simple manner that the maximum density of water is at 4° C. A metal reservoir is fitted about the middle of a tall jar, and two thermometers are inserted, one at the top and the other at the bottom, as shown in Fig. 235. The jar is filled with water at about 10° C., and a freezing-mixture of finely chopped ice and salt is placed in the reservoir. (The reservoir requires constant filling as the experiment proceeds.) Readings of the upper and lower thermometers are taken about every three minutes with results similar to the following:

Upper.....	10	10	10	10	10	10	10	9	8	7	6	5	4	3	2	1	0° C.
Lower.....	10	9	8	7	6	5	4	4	4	4	4	4	4	4	4	4	4° C.

It will be observed that the upper thermometer remains almost stationary while the lower one continues to fall until it indicates a temperature of 4° C. The lower one then remains stationary and the upper one begins to fall and continues to do so until it reaches the freezing-point.

The experiment shows that as the water about the centre of the jar is cooled it becomes denser and continues to descend until all the water in the lower part of the jar has reached the maximum density. When the water in the middle of the jar is cooled further, it becomes lighter and ascends.

204. The Freezing of Lakes. The experiment just described illustrates the behaviour of large bodies of water in

*In an actual experiment the contraction of the glass must be allowed for.

cooling as winter approaches. As the surface layers cool, they become denser and sink, while the warmer water below rises to the top. This process continues until the whole mass of water reaches a uniform temperature of 4° C. The water at the top then expands as it is cooled down to 0° C. and it remains on the surface, where the ice forms and acts as a blanket preventing to a great extent any further loss of heat. Consequently most of the water will have a temperature of 4° C. throughout the winter and at this temperature fish are able to live comfortably.

QUESTIONS AND PROBLEMS

1. Why is water not a suitable liquid to use in a thermometer?

2. Explain where the ice would form and what would happen if water continued to contract down to 0° C., (1) if solidification produced the same expansion as it does now; (2) if contraction accompanied freezing.

3. A certain hot water furnace holds 8 cu. ft. of water at 20° C. What volume will the water occupy at 80° C. if the average coefficient of expansion between these temperatures is 0·00027? How is this expansion provided for?

4. A dilatometer contains exactly 10 c.c. of mercury at 20° C. The mercury is then heated to 100° C. and the volume is 10·144 c.c. Find the coefficient of expansion of mercury. Neglect the expansion of the glass.

5. A specific gravity bottle weighing 15·0 g. was filled with glycerine at 0° C. and the whole then weighed 65·0 g. It was allowed to stand in water at 60° C. and some of the glycerine escaped by overflowing. On weighing again, it weighed 63·5 g. Find the coefficient of expansion of glycerine. (Neglect the expansion of the bottle.)

CHAPTER XXXIII

EXPANSION OF GASES—CHARLES' LAW

205. Coefficient of Expansion of Gases—Charles' Law. It has been shown by the experiments of Charles, Gay-Lussac, Regnault,* and other investigators, that under constant pressure all gases expand equally for equal increases in temperature. In other words, all gases have approximately the same coefficient of expansion. Further, it was shown by Charles, that under constant pressure the volume of a given mass of gas increases by a constant fraction of its volume at 0° C. for each rise of 1 Cent. degree in its temperature. Charles roughly determined this ratio, which was afterwards more accurately measured by Gay-Lussac, whose researches were published in 1802.

The general statement of the principle is usually known as Charles' Law, but sometimes as Gay-Lussac's Law. It is given in the following statement: **The volume of a given mass of any gas at constant pressure increases for each rise of 1 Centigrade degree by a constant fraction (about of its volume at 0° C.**

206. Experimental Verification of Charles' Law. An approximate verification of this law may be made thus:

Experiment. Take a piece of capillary tubing of uniform bore (Fig. 236), about 60 cm. in length, sealed at one end. By careful heating introduce a thread of mercury with enough dry air below it to occupy about half the length of the tube at the ordinary room temperature. Keep the tube in a vertical position, and thus have the inclosed air under con-

FIG. 236.—Apparatus for measuring the expansion of a gas.

*Charles (1746-1823), Gay-Lussac (1778-1850), Regnault (1810-1878) were all French scientists.

stant pressure. Attach the tube and thermometer to a meter stick, immerse them in melting ice, and when the mercury has come to rest read the length of the air column. Now replace the ice-and-water with hot water, stirred so that the temperature is the same throughout. When the mercury has come to rest again read the length of the air column and also the temperature. (The apparatus is somewhat imperfect because the mercury sticks to the tube.)

Let the length of the air column at 0° C. be 20 cm. and 80° C. let it be 25·8 cm. Then since the tube is of uniform bore, the volumes of the air at the different temperatures are proportional to the lengths of the column. Let the area of the cross-section of the tube be x sq. cm.

Then $20x$ c.c. of air when heated through 80 Centigrade degree
expands $5\cdot 8x$ c.c., and therefore
1 c.c. of air when heated through 1 Centigrade degree

$$\text{expands } \frac{5\cdot 8x}{20x \times 80} = \frac{1}{276} \text{ c.c. (approx.)}$$

In this experimemt no correction has been made for the expansion of the glass. It requires very careful work with much more complicated apparatus to obtain the accepted result·

207. Absolute Temperature. Since the volume of a given mass of gas, for each degree of rise in temperature, increases by $\frac{1}{273}$ of its volume at 0° C., it follows that the volume at 1° C. will be $\frac{274}{273}$ of its volume at 0° C. At 2° C. the volume of the gas will be $\frac{275}{273}$ of its volume at 0° C.; and so on.

If the temperature falls to – 1° C. the volume will be diminished $\frac{1}{273}$ and the gas will now occupy a volume of of its volume at 0° C.; at – 2° C. the volume will be ·; at – 100° C. it will be $\frac{173}{273}$; and so on.

From this line of reasoning the volume would disappear at – 273° C. But before reaching such a low temperature the gas would change to a liquid and Charles' Law could no longer be applied.

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*For an account of Regnault's method of determining this coefficient see Edser's *Heat for Advanced Students*, Chapter V.

However, calculations based on the kinetic theory of gases (§ 160) lead to the conclusion that at − 273° C. the rectilinear motions of the molecules would cease; which would mean that the substance was completely deprived of heat and at the lowest possible temperature. This point is hence called the **absolute zero,** and temperature reckoned from it is called **absolute temperature.** Thus a Centigrade reading can be converted into an Absolute reading by adding 273 to it algebraically. For example: 20° C. = 293° A.; − 20° C. = 253° A.

The lowest temperature which has actually been reached is about 0·5 degree above absolute zero.

The method of measuring temperature on an absolute scale was proposed by Lord Kelvin in 1848.

208. Further Statement of Charles' Law. Let us take *any* volume of gas, say 273*a* c.c. at 0° C. and tabulate some of the volumes which it would occupy at various temperatures, when under constant pressure:

VOLUMES	TEMPERATURES	
373*a* c.c.	100° C.	373° A.
283*a* c.c.	10° C.	283° A.
274*a* c.c.	1° C.	274° A.
273a c.c.	**0° C.**	**273° A.**
272*a* c.c.	− 1° C.	272° A.
253*a* c.c.	− 20° C.	253° A.
73*a* c.c.	− 200° C.	73° A.
?	− 273° C.	0° A.

It is immediately evident that the ratio of any two volumes is equal to the ratio of the corresponding absolute temperatures.

We may, therefore, re-state Charles' Law as follows:

If the pressure is kept constant, the volume of a given mass of gas varies directly as the absolute temperature.

This manner of stating the law is often convenient for purposes of calculation.

209. Effect of Temperature on the Pressure of a Gas. If we heat a gas but do not permit it to expand, then the pressure rises. This may easily be shown by attaching a pressure gauge to a pyrex florence flask or a metal vessel (Fig. 237). When the vessel is heated the gauge at once records an increase in pressure.

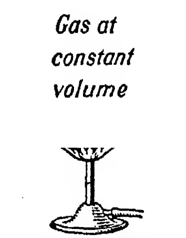


FIG. 237. — Effect of temperature on the pressure of a gas.

It has been shown that in such a case, where the volume remains constant, the pressure of a given mass of gas increases by the same constant fraction (about $\frac{1}{273}$) of its pressure at 0° C. for each rise in temperature of 1° C. That is to say, **the volume-coefficient, and the pressure-coefficient of a gas are numerically equal.** Practically, this is but a statement, in other terms, of the fact that in obeying Charles' Law gases also obey Boyle's Law.

We may state this conclusion in terms of the absolute scale as follows:

If the volume is kept constant the pressure of a given mass of gas varies directly as the absolute temperature.

210. Worked Examples. 1. A mass of gas occupies a volume of 1,000 c.c. at 12° C. What volume will it occupy at 126° C., if the pressure remains constant?

Volume	Temperature	
1,000 c.c.	12° C.	285° A.
	126° C.	399° A.

$$\text{New volume} = 1{,}000 \times \frac{399}{285} = 1{,}400 \text{ c.c.}$$

2. A mass of hydrogen gas occupies a volume of 380 c.c. at a temperature of 12° C. and 80 cm. pressure. What volume will it occupy at a temperature of − 45° C. and a pressure of 76 cm.?

Volume	Temperature		Pressure
380 c.c.	12° C.	285° A.	80 cm.
?	− 45° C.	228° A.	76 cm.

(1) Change in volume for change in temperature.

Since the volume varies directly as the absolute temperature and the temperature is reduced from 285° A. to 228° A. the volume will be reduced to become $\frac{228}{285}$ of the original volume.

(2) Change in volume for change in pressure.

Since the volume varies inversely as the pressure (Boyle's Law) and the pressure is reduced from 80 cm. to 76 cm., the volume will be increased to become $\frac{80}{76}$ of the original volume.

Hence, taking into account the changes for both temperature and pressure,

$$\text{New volume} = 380 \times \frac{228}{285} \times \frac{80}{76} = 320 \text{ c.c.}$$

3. The volume of a mass of oxygen is 1,000 c.c. at 27° C. At what temperature will its volume be 1,200 c.c., the pressure remaining constant?

Let the new temperature = x° A.

Volume	Temperature	
1,000 c.c.	27° C.	300° A.
1,200 c.c.		x°

1,200

Whence $x = 360$ and the temperature = 360° A. or 87° C.

PROBLEMS

1. If the absolute temperature of a given mass of gas is doubled while the pressure is kept constant, what change takes place in (*a*) its volume, (*b*) its mass, (*c*) its density?

2. The pressure of a given mass of gas was doubled while its volume remained constant. What change must have taken place in (*a*) its absolute temperature, (*b*) its density?

3. The pressure remaining constant, what volume will a given mass of gas occupy at 75° C. if its volume at 0° C. is 22·4 litres?

4. If the volume of a given mass of gas is 120 c.c. at 17° C., what will be its volume at − 13° C.?

5. A gauge indicates that the pressure of the oxygen gas in a steel gas tank is 150 pounds per square inch when the temperature is 20° C. Supposing the capacity of the tank to remain constant, find the pressure of the gas at a temperature of 30° C.

6. An empty bottle, open to the air, is corked when the temperature of the room is 18° C. and the barometer indicates a pressure of 15 pounds per square inch. Neglecting the expansion of the bottle, find the pressure of the air within it after it has been standing for some time in a water bath whose temperature is 67° C.

7. The volume of a given mass of gas is one litre at a temperature of 5° C. The pressure remaining constant, at what temperature will its volume be (*a*) 1,100 c.c., (*b*) 900 c.c.?

8. At what temperature will the pressure of the air in a bicycle tire be 33 pounds to the square inch, if its pressure at 0° C. is 30 pounds per square inch? (Assume no change in volume.)

9. A mass of oxygen gas occupies a volume of 120 litres at a temperature of 20° C. when the barometer stands at 74 cm. What volume will it occupy at standard temperature and pressure? (0° C. and 76 cm. pressure.)

10. The volume of a certain mass of gas is 500 c.c. at a temperature of 27° C. and a pressure of 400 grams per sq. cm. What is its volume at a temperature of 17° C. and a pressure of 600 grams per sq. cm.?

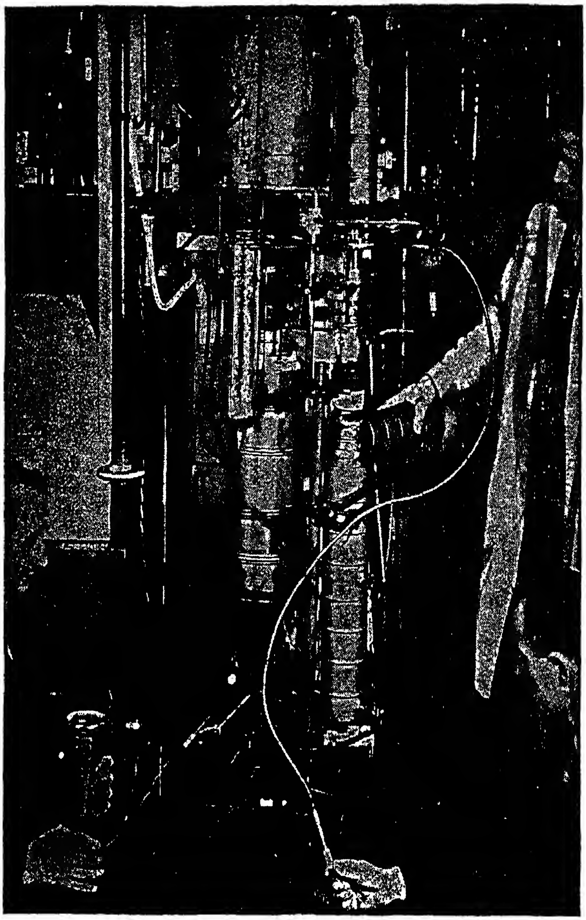
11. A mass of gas occupies 300 c.c. under a pressure of 760 mm. of mercury when at 27° C. What will the pressure become if the volume is kept constant while the temperature is raised to 327° C.?

12. A volume of gas is heated from 27° C. to 927° C., while at the same time the external pressure is raised from 15 to 60 pounds. per square inch. How is the volume affected?

13. If one gram of a gas at 50° C. and under a pressure of 76 cm. of mercury has a volume of 800 c.c., what will be its volume at 84° C. when the pressure on it is 64 cm. of mercury?

14. The pressure upon a quantity of gas in a cylinder with a movable piston is changed from 3 to 5 atmospheres while at the same time the temperature is changed from 20° C. to 320° C. What is the ratio of the new to the old volume?

15. The weight of a litre of air at standard temperature and pressure is 1·29 grams. Find the weight of 800 c.c. of air at 37° C. and 70 cm. pressure.



APPARATUS FOR LIQUEFYING HELIUM GAS
In the Low Temperature Laboratory of the University of Toronto

The experimenter at the left holds a vacuum flask containing liquid air which is at $-191°$ C.; one at the right is pouring liquid air into a jacket surrounding a tube containing liquid helium which at atmospheric pressure is at a temperature of $-269°$ C. The third experimenter is making observations for the determination of the index of refraction of liquid helium.

CHAPTER XXXIV

MEASUREMENT OF HEAT

211. Unit of Heat. As already pointed out (§ 190), the *temperature* of a body is to be distinguished from the *quantity of heat* which it contains. The thermometer is used to determine the temperature of a body, but its reading does not give the quantity of heat possessed by it. A gram of water in one vessel may have a higher temperature than a kilogram in another, but the latter will contain a greater quantity of heat. Again, a pound of water and a pound of mercury may be at the same temperature, but we have reasons for believing that the water contains more heat.

In order to measure heat we must choose a suitable unit, and, by common consent, the amount of heat required to raise by one degree the temperature of a unit mass has been selected as the most convenient one. The unit, will, of course, have different magnitudes, varying with the units of mass and temperature-difference chosen. In connection with the metric system the unit called the **calorie** has been adopted for scientific purposes. **The calorie is the amount of heat required to raise a mass of one gram of water one Centigrade degree in temperature.**

For example,

to raise 1 gram of water through 1 Cent. deg. requires 1 calorie,
to raise 4 grams of water through 5 Cent. deg. requires 20 calories,
and to raise m grams of water from $t_1°$ to $t_2°$ C. requires $m\ (t_2 - t_1)$ calories.

In engineering practice, the **British thermal unit** (designated B.T.U.) is in common use in English-speaking countries. **The British thermal unit is the quantity of heat required to raise one pound of water one Fahrenheit degree in temperature.**

The calorie used in stating food values is the amount of heat required to raise 1 kilogram of water 1 Centigrade degree. It is 1,000 times as large as the calorie defined above.

PROBLEMS

1. How many calories of heat must enter a mass of 65 grams of water to change its temperature from 10° C. to 35° C.?

2. How many calories of heat are given out by the cooling of 120 grams of water from 85° C. to 60° C.?

3. If 1,400 calories of heat enter a mass of 175 grams of water, what will be its final temperature, supposing the original to be 15° C.?

4. A hot-water coil containing 100 kilograms of water gives off 1,000,000 calories of heat. Neglecting the heat lost by the iron, find the fall in the temperature of the water.

5. On mixing 65 grams of water at 75° C. with 85 grams at 60° C., what will be the temperature of the mixture?

First Solution—

Let x° C. be the resulting temperature of the mixture. Then the hot water falls in temperature $(75 - x)$ deg., and the cold water rises $(x - 60)$ deg.

Heat lost by the hot water $= 65\ (75 - x)$ cal.

Heat gained by the cold water $= 85\ (x - 60)$ cal.

These quantities are equal and hence

$65\ (75 - x) = 85\ (x - 60)$, and $x = 66{\cdot}5°$ C.

Second Solution—

When cooling to 0° C. the hot water would give out 65×75 cal.

When cooling to 0° C. the cold water would give out 85×60 cal.

Total heat given out $= 65 \times 75 + 85 \times 60$ cal.

The same amount of heat would be given out when the total mass, or 150 gm., should fall from x° C. to 0° C. This heat $= 150x$ cal.

Hence $150x = 65 \times 75 + 85 \times 60$, and $x = 66{\cdot}5°$ C.

6. Find the resulting temperature when 100 grams of water at 20° C., 200 grams at 35° C. and 300 grams at 60° C. are mixed together.

7. On mixing 300 grams of water at 80° C. with 500 grams at an unknown temperature the resulting temperature was 36° C. What was the unknown temperature?

8. What will be the resulting temperature on mixing 400 grams of water at 10° C., 100 at 20° C., 300 at 60° C. and 200 at 80° C.?

9. One pound of a certain sample of coal contains 12,000 B.T.U. If the heat from it is applied to 120 pounds of water at 60° F., to what temperature will it be raised, assuming that one-half of the heat from the coal is lost?

10. If coal of heat value 14,000 B.T.U. per pound can be bought at $10 per ton, what price per cord should be paid for wood of heat value 8,000 B.T.U. per pound, in order that the cost for heating should be the same in the two cases. (Assume that 1 cord of wood weighs 3,500 pounds.)

212. Specific Heat. Let us take three precisely similar beakers and pour 200 grams of water into the first, 200 grams of coal oil in the second and 200 grams of mercury in the third. The volumes of these substances will be 200 c.c., 250 c.c. and 14·7 c.c., respectively.

Place the first beaker on the sand in a sand-bath which has been over a small Bunsen flame for some time and has become heated through (Fig. 238). Let it stay there for 30 sec. and observe the rise in temperature. Let it be 2°. Next, place the second beaker on for the same length of time, The rise in temperature will be about 4°, or 2 times as great. Finally, put the third beaker on for the same length of time. The rise in temperature will actually be 60°, or thirty times as great.

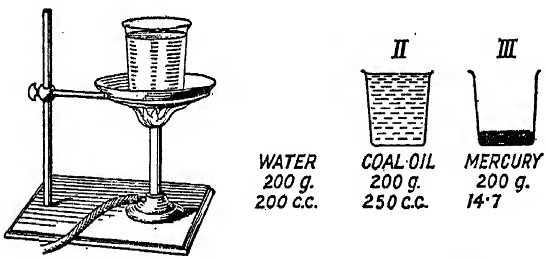


FIG. 238.—The same amount of heat is applied to the same mass of water, coal oil and mercury.

Now the same amount of heat has been applied to each substance, and so it is clear that in order to heat a given mass of coal oil through a certain number of degrees one need use only $\frac{1}{2}$ the amount of heat required to heat the same mass of water through the same rise in temperature,

while to heat the same mass of mercury through the same rise in temperature, only $\frac{1}{30}$ as much heat is required as in the case of water. We see then that

To raise 1 gm. of water through 1 Cent. deg. requires 1 calorie,
To raise 1 gm. of coal oil through 1 Cent. deg. requires $\frac{1}{2}$ calorie,
To raise 1 gm. of mercury through 1 Cent. deg. requires $\frac{1}{30}$ calorie.

Taking water as the standard substance, we say that the **specific heat** of water is 1, that of coal oil is $\frac{1}{2}$, and that of mercury is $\frac{1}{30}$.

The specific heat of a substance is equal to the number of heat units required to raise the temperature of a unit mass of the substance one.

When we say that the specific heat of iron is 0·113 we mean that it takes

0·113 calorie of heat to raise 1 gm. of iron 1 Cent. deg.
or 0·113 B.T.U. of heat to raise 1 lb. of iron 1 Fah. deg.

Hence, the quantity of heat required to warm a mass of m grams of a substance from a temperature of $t_1°$ C. to a temperature of $t_2°$ C. $= m\ (t_2 - t_1)\ s$ calories, when s is the specific heat of the substance.

PROBLEMS

1. How much heat is required to raise the temperature of 350 grams of coal oil from 20° C. to 90° C.?

2. Calculate the amount of heat required to raise 500 c.c. of coal oil from 15° C. to 45° C. (Density of coal oil, 0·8 grams per c.c.)

3. Find how much heat is required to raise 500 grams of mercury from − 15° C. to 175° C.?

4. How much heat is required to raise 100 c.c. of mercury from 20° C. to 200° C.? (For density of mercury see Table on page 17.)

5. If the specific heat of iron is 0·113, calculate the amount of heat in B.T.U. to raise the temperature of an iron radiator weighing 500 pounds and the 200 pounds of water which it contains from 10° C. to 85° C.

213. Capacity for Heat. Of all known substances except hydrogen, water has the greatest capacity for heat, which

fact is of great importance in the distribution of heat on the surface of the earth. For example, land areas surrounded by large bodies of water are not so subject to extremes of temperature. In summer the water absorbs the heat, and, as it warms very slowly, it remains cooler than the land. In winter, on the other hand, the water gradually gives up its store of heat to the land, thus preserving an equable temperature.

The thermal capacity of a body is defined to be the number of heat units required to raise its temperature one degree.

For example, consider a brass cylinder weighing 50 gm. The specific heat of brass is 0·090 and consequently the thermal capacity of the cylinder is $50 \times 0 \cdot 090 = 4 \cdot 5$ calories.

This quantity of heat would raise the temperature of 4·5 gm. of water 1 Centigrade degree, and hence we say that the water equivalent of 50 gm. of brass is 4·5 gm.

The water equivalent of a body is the mass of water which has the same thermal capacity as the body.

214. Determination of Specific Heat by the Method of Mixture. The simple method of showing that different substances have different specific heats, described in § 212, involves too many sources of error to be used for the accurate determination of specific heats. For this the method of mixture, already illustrated in the problems in § 211, is usually employed.

When a hot and a cold body are placed in contact the hot body gives up its heat to the cold one until both come to the same temperature. Then, if no heat has been lost to, or gained from, external objects, it is evident that the amount of heat lost by the hot body is equal to the amount of heat gained by the cold body.

For example, suppose a 500-gm. block of lead at 100° C. is placed in 100 gm. of water at 13° C. and the resulting temperature is 25° C.

Let the specific heat of lead $= x$.

Then, heat given out by the lead $= 500 \times (100 - 25) \times x$ calories.

And, heat gained by the water $= 100 \times (25 - 13) \times 1$ calories.

Hence, if we assume that all of the heat lost by the lead was gained by the water,

$$500 \times (100 - 25) \times x = 100 \times (25 - 13) \times 1,$$

$$\text{Whence} \qquad x = 0 \cdot 032.$$

It is evident, however, that we should allow for the heat gained by the vessel containing the water and that special precautions must be adopted to prevent heat being lost to, or gained from, the air or other external objects.

PROBLEMS

(For specific heats see table in § 217)

1. What is the thermal capacity of a glass beaker whose mass is 35 grams?

2. Which has the greater thermal capacity, 68 grams of mercury or 2 grams of water?

3. It requires 360 calories of heat to raise the temperature of a body 10 degrees. What is its thermal capacity? Its water equivalent?

4. The thermal capacity of 56 grams of copper is 5·264 calories. What is the specific heat of copper?

5. It requires 902·2 calories of heat to warm 130 grams of paraffin from 0° C. to 10° C. What is the specific heat of paraffin?

6. How much heat will a body whose thermal capacity is 320 calories lose in cooling from 40° C. to 10° C.?

7. What is the quantity of heat required to raise 120 grams of aluminium from 15° C. to 52° C.?

8. How many calories of heat are given off by an iron radiator whose mass is 25 kg., in cooling from 100° C. to 20° C.

9. A lead bullet whose mass is 12 grams had a temperature of 25° C. before it struck an iron target, and a temperature of 100° C. after impact. How many calories of heat were added to the bullet?

CHAPTER XXXV

CALORIMETERS AND THEIR USE

215. Calorimeters. The vessel used in making heat measurements by the method of mixture is called a **calorimeter.** Glass vessels wrapped with a towel or with batting are not very satisfactory; they are easily broken, and besides are slow in taking the temperature of the water or other liquid which they hold.

The best calorimeters are of polished metal and it is well to have the vessel containing the water within a larger one as shown in Fig. 239.

Here a polished vessel A is supported within the outer polished vessel B by a fibre ring C. The vessels are polished to minimize absorption or radiation of heat, and the air space between the vessels acts as a heat insulator. The fibre ring is also a poor conductor of heat. A wooden cover with a hole for the thermometer T is sometimes provided but beginners usually find it a hinderance rather than a help. In the diagram the inner vessel contains water and a metal block whose specific heat is being found.

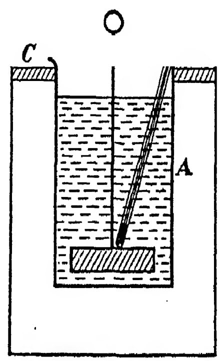


Fig. 239.—A calorimeter. A and B, polished metal vessels; C, a fibre ring supporting A.

216. Specific Heat of Solids. Suppose we wish to find the specific heat of lead. It is convenient to have the lead in the form of a block with a wire handle but a piece of string may replace the handle. The procedure is as follows:

Experiment. 1. Weigh the lead block.

2. Heat the lead block in water in a beaker and take the temperature of the water when it boils.

3. Weigh the inner vessel of the calorimeter which we suppose is of copper ($S.H. = 0 \cdot 094$).

4. Put about 100 gm. of *cold* tap water in the inner vessel and weigh again, to find the weight of the water.

5. Place the inner vessel in the outer and take the temperature of the water carefully.

6. Quickly transfer the lead block from the boiling water to the calorimeter, move it about in the cold water to stir it and record the temperature as soon as it is steady.

Observations—

Weight of lead	500 gm.
Temperature of boiling water and lead	100° C.
Weight of inner vessel	80 gm.
Weight of cold water	100 gm.
Temperature of cold water and inner vessel	14° C.
Temperature of water, inner vessel and lead after mixing	25° C.

Calculations—

Let x be the specific heat of lead.

Heat given out by lead $= 500 \times 75 \times x$ calories

Heat gained by water $= 100 \times 11 \times 1$ calories

Heat gained by calorimeter $= 80 \times 11 \times \cdot 094$ calories

Total heat gained $= 1100 + 82 \cdot 7 = 1182 \cdot 7$ calories

Heat given out = heat gained

Hence $37500x = 1182 \cdot 7$

and $x = \cdot 031$

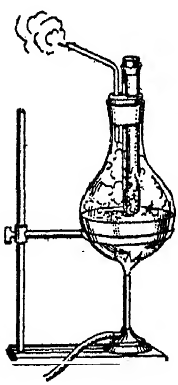


FIG. 240.—Determination of specific heat of a solid.

When many experiments are being performed with the same calorimeter the calculation is simplified by finding the water equivalent of the calorimeter. In this case the water equivalent $= 80 \times \cdot 094 = 7 \cdot 52$ gm. and consequently the total heat gained $= (100 + 7 \cdot 52) \times 11 = 1182 \cdot 7$ calories, as before.

If the lead is in small pieces it may be placed in a large test tube and heated as shown in Fig. 240.

217. Specific Heat of Liquids. As a rule, the specific heat of liquids cannot be determined with any degree of accuracy by mixing the liquids with water, because many liquids do not mix readily with water, while others evolve heat when

added to it; but the method of mixtures may be used for this purpose by taking a suitable body of known specific heat and dropping it into the liquid whose specific heat is to be determined.

For example, we might find the specific heat of ethyl alcohol by using the apparatus described in the preceding section. The alcohol would be placed in the inner vessel instead of water and we should have to know the specific heat of the lead. Then the heat given up by the hot lead would be equal to the heat gained by the calorimeter and the alcohol.

Exercise. A 500-gm. block of lead is heated to 75° C. and transferred to a copper calorimeter weighing 80 gm. and containing 100 gm. of ethyl alcohol at 15° C. The resulting temperature is 55° C. Find the specific heat of the alcohol (S.H. of lead = 0·031; of copper = 0·094). (Answer = 0·7)

AVERAGE SPECIFIC HEATS OF SOME COMMON SUBSTANCES

Aluminium	0·214	Ice (− 10° C.)	0·50	Paraffin (wax)	0·694
Brass	0·090	Iron	0·113	Petroleum	0·511
Copper	0·094	Lead	0·031	Platinum	0·032
Glass (crown)	0·16	Marble	0·216	Silver	0·056
Glycerine	0·576	Mercury	0·033	Zinc	0·093

218. Specific Heat in Relation to Agriculture. The specific heat of soils is of considerable importance in agriculture. On account of the pores in the soil it is customary to speak of specific heat by unit volume rather than by unit mass. By deep ploughing and thorough cultivation the farmer may lower the volume thermal capacity of his soil and thus make it warm up more quickly in the spring. The addition of humus to the soil tends to produce the same result.

The amount of water present in the soil is, however, the greatest factor in determining whether it will be an "early" or "late" soil. It is therefore important to remove excess water by drainage, as a wet soil is a colder soil in spring than one which is well drained. This is one reason why early vegetables are usually grown on sandy soils.

The proximity of large bodies of water tends to moderate the climate on land areas because water has a higher specific heat than land and hence smaller variations in temperature. Read § 213 and also § 261 on winds.

PROBLEMS

(Table of specific heats in § 217)

1. If 95 grams of a metal are heated to 100° C. and then placed in 114 grams of water at 7° C., the resulting temperature is 15° C. Find the specific heat of the metal? What metal is it?

2. A piece of iron, whose mass is 88·5 grams and temperature 90° C., is placed in 70 grams of water at 10° C. If the resulting temperature is 20° C., find the specific heat of iron.

3. A mass of zinc, weighing 5 kg. and having a temperature of 80° C., was placed in a liquid, and the resulting temperature was found to be 15° C. How much heat did the zinc impart to the liquid?

4. On dropping 100 grams of iron at 200° C. into 600 grams of oil, the temperature of the oil is raised from 15° C. to 20° C. Find the specific heat of the oil.

5. On mixing 1 kg. of a substance having a specific heat of 0·85, at a temperature of 12° C., with 500 grams of a second substance at a temperature of 120° C., the resulting temperature is 45° C. What is the specific heat of the second substance?

6. Find the resulting temperature on placing 75 grams of a substance having a specific heat of 0·8 and heated to 95° C. in 130 grams of a liquid at 10° C. whose specific heat is 0·6.

7. Into 120 grams of water at a temperature of 0° C. 150 grams of mercury at 80° C. are poured. What is the resulting temperature?

8. Find the resulting temperature when 20 grams of iron at 100° C. are immersed in 80 grams of water at 10° C., contained in a copper vessel whose mass is 20 grams.

9. Find the water equivalents of the following:
   (*a*) A copper calorimeter weighing 120 grams.
   (*b*) A glass stirring-rod weighing 20 grams.
   (*c*) A thermometer containing 3 grams of mercury and 10 grams of glass.

CHAPTER XXXVI

CHANGE OF STATE—SOLID TO LIQUID

219. Fusion. Let us take some pulverized ice at a temperature below the freezing-point and apply heat to it. It gradually rises in temperature until it reaches 0° C., when it begins to melt. If the ice and the water formed from it are kept well stirred, no sensible change in temperature takes place until all the ice is melted. On the further application of heat the temperature begins again to rise.

The change from the solid to the liquid state by means of heat is called **fusion or melting,** and the temperature at which fusion takes place is called the **melting-point.**

The behaviour of water is typical of **crystalline substances** in general. Fusion takes place at a temperature which is constant for the same substance if the pressure remains unchanged. **Amorphous bodies,** on the other hand, have no sharply defined melting-points. When heated, they soften and pass through various stages of plasticity into more or less viscous liquids, the process being accompanied by a continuous rise in temperature. Roofing-pitch, glass and wrought-iron are typical examples. By a suitable control of the temperature glass can be bent, drawn out, moulded or blown into various forms, and iron can be forged, rolled or welded.

220. Solidification. The temperature at which a substance solidifies, the pressure remaining constant, is the same as that at which it melts. For example, if water is gradually cooled, while it is kept agitated, it begins to take the solid form at 0° C., and it continues to give up heat without falling in temperature until the process of solidification is complete.

But it is interesting to note that a liquid which under ordinary conditions solidifies at a definite point may, if slowly and carefully cooled, be lowered several degrees below its normal temperature of solidification. The phenomenon is illustrated in the following experiment.

Experiment. Pour some pure water, boiled to free it from air bubbles, into a test-tube. Close the tube with a perforated stopper, through which a thermometer is inserted into the water. Place the tube in a freezing mixture of ice and salt. If the water is kept quiet, it may be lowered to a temperature of − 5° C. without freezing. It is said to be *supercooled*, but the condition is unstable. If the water is agitated or crystals of ice are dropped in, it suddenly turns into ice and the temperature rises to 0° C.

MELTING-POINTS OF SOME SUBSTANCES

Substance	M. P.	Substance	M. P.	Substance	M. P.
Aluminium.	659° C.	Iron (pure)	1530° C.	Silver.....	960° C.
Cobalt....	1480	Lead......	327	Sulphur...	115
Copper....	1083	Mercury...	−39	Tin.......	232
Gold......	1063	Nickel....	1452	Tungsten..	3400
Iridium....	2350	Platinum..	1755	Zinc......	419

221. Change of Volume on Solidification. The expansive force of ice in freezing is well known to all who live in cold climates. The appearance of a bottle of frozen milk is a familiar sight in very cold weather. Water must be replaced by anti-freeze in the cooling system of an automobile in winter to prevent serious damage to the engine and radiator. A field which is to be sown in the spring is often ploughed in the fall. The water between the particles of soil freezes and expands during the winter, thus loosening the soil so that it is in excellent condition for working in the spring. This action of frost is also an important agency in the weathering of rocks. Water seeps into minute crevices in the rocks and when it freezes disintegration of the rock occurs.

If we pour some melted paraffin into a beaker and allow it to cool and solidify it will be found that the surface is distinctly concave. Even a large drop of melted paraffin will show a dimple on the surface when it has solidified. These experiments indicate that the wax contracts on solidifying. A lump of solid wax will sink in the liquid wax whereas a lump of ice floats on water.

Most substances undergo a decrease in volume in passing from the liquid to the solid state; but some which are crystalline in structure, such as ice, bismuth and antimony, are exceptions to the rule. (Even these substances when in the solid state contract on being cooled.)

Only from metals which expand on solidification can perfectly shaped castings be obtained. The reasons are obvious. Antimony is added to lead and tin to form type-metal because the alloy thus formed expands on solidifying and conforms completely and sharply with the outlines of the mould. Gold and silver coins must be stamped from the solid metal because these metals contract when they solidify, as do most other metals and alloys.

222. Influence of Pressure on Melting-point. Let us consider water at 0° C. completely filling a strong closed vessel, such as a piece of iron pipe with a cap screwed on each end. If the temperature is steadily lowered what will happen? Since the water expands when it changes to ice and the closed vessel holds back the expansion, it is evident that a temperature below zero—the ordinary freezing-point of water—must be reached before freezing takes place, and when it does so the vessel will burst. Again if ice be put into a strong vessel and great pressure be exerted on it, the pressure will tend to compress the ice into water and melting will take place below the ordinary freezing-point.

On the other hand wax expands when it melts and pressure exerted on it would retard melting, and to melt the wax would require a higher temperature; while if the wax is

solidifying pressure on it would assist the process and it would solidify at a temperature above the ordinary melting-point.

We then conclude: **If a substance contracts on melting, its melting-point will be lowered by pressure, while if it expands, its melting-point will be raised.**

It requires an enormous pressure to make any appreciable change in the melting-point.

Experiment. An interesting experiment shows the effect of pressure on the melting-point of ice. Take a block of ice and rest it on two supports, and encircle it with a fine wire from which hangs a heavy weight (Fig. 241). In a few hours the wire will cut its way through the ice, but the block will still be intact. Under the pressure of the wire the ice melts, but the water thus formed is below the normal freezing-point. Hence it flows above the wire and freezes again, as the pressure there is normal. The process of melting and freezing again under these conditions is called **regelation.**

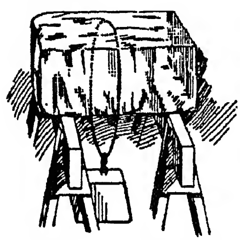


Fig. 241.—Regelation of Ice.

QUESTIONS

1. Two pieces of cast iron can be joined together by the oxy-acetylene flame. How does this process differ from the blacksmith's welding?

2. A piece of solid metal floats on the surface of the liquid metal. Does the metal expand or contract on solidifying? Explain.

3. When a person packs a snowball sufficiently it becomes a lump of ice. Explain. What must the temperature be in order to have the snow pack well?

4. Account for the smooth track seen behind a sleigh in winter.

5. Why do sharp skates "take hold" of the ice better than dull ones?

6. If two pieces of ice are pressed together under the surface of warm water, they will be found to be frozen together on removing them from the water. Account for this.

7. Antarctic explorers report that it is extremely difficult to pull a sled through snow when the temperature is very low. Suggest a reason.

8. Why should a fine wire rather than a metal band be used in the experiment shown in Fig. 241?

223. Heat of Fusion. We have learned (in § 219) that during the process of melting a crystalline body such as ice, no change in temperature takes place, although heat is being continuously applied to it. In earlier times, when heat was considered to be a kind of substance, it appeared that the heat applied became hidden in the body, and it was called **latent heat.**

According to modern ideas, there is simply a transformation of energy. When a body in fusing ceases to rise in temperature, although heat is still being applied, the heat-energy is no longer occupied in increasing the average kinetic energy and to some extent the potential energy of its molecules, but is doing work in overcoming the cohesive forces which bind these molecules together in the body as a solid.

A definite quantity of heat, varying with the substance, is required to melt a definite mass of a solid. **The amount of heat required to melt one gram of a substance without a change of temperature is called its heat of fusion.** For example, the heat of fushion of ice is 80 calories, which means that 80 calories of heat are required to melt one gram of ice.

224. Determination of Heat of Fusion of Ice. The method of mixture (§ 214) may be used to determine the heat of fusion of ice. For example, let 100 gm. of dry snow or finely broken ice at 0° C. be dropped into 390 gm. of water at 45° C. contained in a calorimeter whose water equivalent is 10 gm. If the mixture is stirred until all the ice is melted it will be found that the resulting temperature is about 20° C.

In our calculation we may consider the water and calorimeter together as equivalent to 400 gm. of water at 45° C.

Let the heat of fusion of ice be x calories.

1. *Heat received*—

To melt the ice .... $100x$ cal.
To raise resulting water from 0° C. to 20° C. .... 100×20 cal.

2. Heat given out—

400 gm. water falling from 45° C. to 20° .... 400×25 cal.

$$\text{Heat received} = \text{Heat given out.}$$

Therefore $100x + 100 \times 20 = 400 \times 25$,

from which $x = 80$ cal.

It requires 80 calories of heat to melt 1 gm. of ice at 0° C.

Heat of Fusion of a Few Substances

M.P., Melting Point; H. of F., Heat of Fusion.

Substance	M. P.	H. of F.	Substance	M. P.	H. of F.
Iron, gray cast.	1200° C.	23	Paraffin Wax..	52° C.	35
Ice...........	0	80	Silver........	960	21
Lead..........	327	5·4	Sulphur......	115	9·4
Mercury......	−39	2·8	Zinc.........	419	28

225. Heat given out on Solidification. All the heat required to melt a certain mass of a substance without change in temperature is given out again in the process of solidification. Thus, every gram of water, in freezing, sets free 80 calories of heat. The formation of ice tends to prevent extremes of temperature in our lake regions. Heat is given out in the process of freezing during the winter, and absorbed in melting the ice in spring and early summer.

226. Heat Absorbed in Solution; Freezing Mixtures. In cases of ordinary solution, as in dissolving sugar or salt in water, heat is absorbed. If a handful of salt is dropped into a beaker of water at the temperature of the room, and the mixture is stirred with a thermometer, the mercury will be seen to drop several degrees.

The result is much more marked if ice and salt are mixed together. Both become liquid, forming brine, and in the process of changing from solid to liquid both substances require heat. This heat is taken from the resulting solution and from surrounding objects, so that their temperatures fall.

This is the principle applied in preparing freezing mixtures. The ordinary freezing mixture of ice and salt can be made to give a temperature of about $-22°$ C.

The freezing point of a solution is lower than that of pure water. For example the freezing-point of sap in trees is lower than that of water and consequently the temperature must fall considerably below 0° C. to injure the trees or buds.

QUESTIONS AND PROBLEMS

1. Water is sometimes placed in cellars to keep vegetables from freezing. Explain the action.

2. Why is a quantity of ice at 0° C. more effective as a cooling agent than an equal mass of water at the same temperature?

3. Explain how the presence of ice keeps the contents of a refrigerator cool.

4. A mixture of crushed ice and water is poured into a vessel containing a thermometer. What will be the effect on the reading of the thermometer when (*a*) more water is poured in, (*b*) more ice is put in, (*c*) salt is stirred in? Give reasons in each case.

5. If we pour just enough cold water on a mixture of ammonic chloride and ammonic nitrate to dissolve them, and stir the mixture with a small test-tube, into the bottom of which has been poured a little cold water, the water in the tube will be frozen. Explain.

6. What quantity of heat is required to melt 35 grams of ice at 0° C.?

7. How much heat is given off by the freezing of 15 kg. of water?

8. How much heat is required to change 23 grams of ice at $-10°$ C. to water at 10° C.? (Specific heat of ice $= 0 \cdot 5$.)

9. What mass of water at 80° C. will just melt 80 grams of ice?

10. Fifty grams of ice are placed in 520 grams of water at $19 \cdot 8°$ C. and the temperature of the whole becomes $11 \cdot 1°$ C. Find the heat of fusion of ice.

11. Sixty grams of ice are placed in 240 gm. of water at 35° C. and the resulting temperature after all the ice is melted is 12° C. Find the heat of fusion of ice.

12. What is the specific heat of brass if a mass of 80 grams at a temperature of 100° C. just melts 9 grams of ice?

13. How much ice must be placed in a pail containing 10 kg. of drinking water at 20° C. to reduce the temperature to 10° C.?

14. What mass of water at 75° C. will convert 120 grams of ice into water at 10° C.?

15. What mass of ice must be dissolved in a litre of water at 4° C. to reduce the temperature to 3° C.?

16. Find the resulting temperature when 40 grams of ice are dropped into 180 grams of water at 90° C.

17. Find the number of B.T.U.'s required to melt 1 pound of ice at the melting-point.

18. How many B.T.U.'s are needed to change 100 pounds of ice at 20° F. to water at 182° F.?

CHAPTER XXXVII

CHANGE OF STATE—LIQUID TO VAPOUR

227. Vaporization. Transition from a liquid to a vapour is a familiar phenomenon. Water in a shallow dish exposed to a dry atmosphere gradually changes to a vapour and disappears in the air. If heat is applied and the water is made to boil, the change takes place more rapidly. The process of converting a liquid into vapour is called **vaporization.** The quiet vaporization taking place at all temperatures at the surface of a liquid is known as **evaporation.**

In **ebullition,** or **boiling,** the production of vapour takes place throughout the mass, and the process is accompanied by an agitation of the liquid, due to the formation of bubbles of vapour within the liquid and their movement upward to the surface. A liquid boils at a *definite* temperature if the pressure is kept constant.

228. Rate of Evaporation. The rate of evaporation depends on many conditions:

(1) *The nature of the liquid.* A little ether placed on the palm of the hand disappears almost at once and distinctly cools the skin. Water would keep the hand wet for a considerable time. Some dense oils can scarcely be said to evaporate at all. Liquids which evaporate readily are said to be *volatile.*

(2) *The temperature of both the liquid and the air.* Wet clothes and wet roads dry more rapidly on a warm day than on a cold one, if the atmosphere is equally dry on the two days.

(3) *The dryness of the air.* If there is much vapour already in the air, the evaporation is slower.

(4) *The extent of free surface of the liquid.* With a large surface the evaporation is greater than with a small one.

(5) *The renewal of the air over the liquid.* If a breeze is blowing, evaporation is more rapid. Wet articles dry very rapidly on a windy day.

(6) *The pressure exerted on the liquid.* Lowering the pressure increases the rate of evaporation.

The molecular explanation of evaporation is given in § 163.

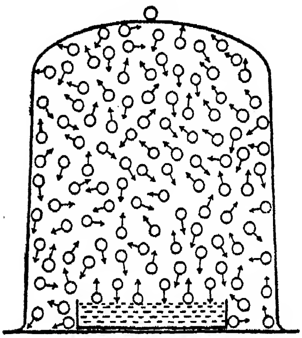


Fig. 242.—Illustrating evaporation.

229. Saturated Vapour. When a liquid is placed in an open dish exposed to free air the process of evaporation continues until all the liquid has disappeared. If, however, the dish is within a closed container (Fig. 242), the inclosed space soon becomes so filled with molecules of the liquid that as many re-enter the liquid as leave it. In this case the space is said to be **saturated** with the vapour of the liquid and the pressure which the vapour exerts is called the **saturation pressure.** This saturation pressure increases with the temperature, and whenever a saturated vapour is cooled or compressed, condensation takes place. For a vapour to be saturated some of the liquid must be present.

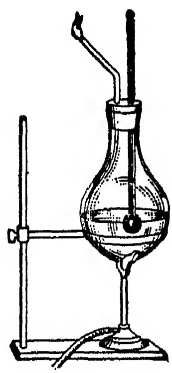


Fig. 243.—Determination ing-point

230. Ebullition—Boiling-point. When heat is applied to water (Fig. 243), it gradually rises in temperature until vapour is disengaged in bubbles from the mass of the liquid; but no further rise in temperature takes place, however rapidly the process of boiling is maintained.

The temperature at which a liquid boils, or gives off bubbles of its own vapour, is called its **boiling-point.**

231. Effect of Pressure on the Boiling-point. The boiling-point varies with the pressure. If the pressure of the escaping steam is increased by leading the outlet-pipe to the bottom of a vessel of water as shown in Fig. 244, the temperature of the boiling water is raised.

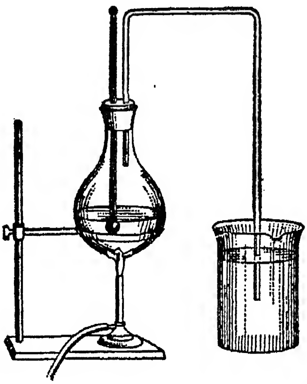


FIG. 244.—Boiling-point of a liquid raised by means of pressure.

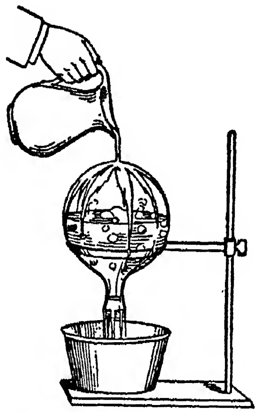


FIG. 245.—Boiling-point of a liquid lowered by decrease of pressure.

To secure a marked effect the vessel containing the water should be deep and if mercury is used instead of water the result is still more pronounced. The experiment may also be performed by attaching a short piece of rubber tubing to the delivery tube and gradually tightening a clamp on the tube. If this is done care should be taken not to "blow up" the apparatus.

On the other hand, a decrease in pressure is accompanied by a lowering of the temperature. This is shown by a familiar but striking experiment:

Half fill a flask with water and boil for a minute or two in order that the escaping steam may carry out the air. While the water is boiling, remove the flame, and at the same instant close the flask with a stopper. Invert the flask and support it on a retort stand (Fig. 245), and pour cold water over the flask. The temperature of the water in the flask is below 100° C., but it boils vigorously. The action is explained as follows. The chilling of the flask condenses the vapour within and thus reduces the pressure on the surface of the water. The water, relieved of this pressure, boils at a lower temperature. If we discontinue the cooling and allow the vapour to accumulate and the pressure to

increase, the boiling ceases. The process may be repeated several times. In fact, if care is taken in expelling the air at the beginning, the water may be made to boil even when the temperature is reduced to that of the room.

This result can also be obtained by heating water in the flask shown in Fig. 244 to (say) 80° C. If the burner is then removed and an exhaust pump connected to the delivery tube, boiling will soon commence and the temperature will drop rapidly.

In the case of liquids liable to burn, evaporation may be produced in "vacuum pans" in which boiling takes place under reduced pressure (and therefore lowered temperature). This arrangement is used, for example, in condensing milk and sugar syrups.

232. Why Pressure Affects the Boiling-point. The reason why the boiling-point depends upon the pressure is readily found. Bubbles of vapour begin to form in the liquid only when the pressure exerted by the vapour within the bubble balances the pressure on the surface of the liquid (Fig. 246). But the pressure of a vapour in contact with its liquid in an inclosed space varies with the temperature. Hence, a liquid will be upon the point of boiling when its temperature has risen sufficiently high for the pressure of the saturated vapour of the liquid to be equal to the pressure sustained by the surface of the liquid. Therefore, when the pressure on the surface is high, the boiling-point must be high, and *vice versa.* The accompanying diagram (Fig. 247) shows graphically the relation between the pressure and the boiling-point of water ranging from 1 to 25 atmospheres.

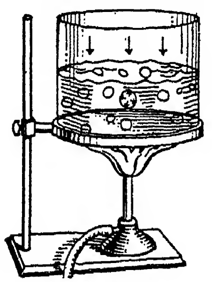


Fig. 246.—Balance be- external pressure he air and xerted by th within bubble.

It is to be noted that the steam bubbles begin in the small air or gas bubbles present in the water, and when these are removed by prolonged boiling, the liquid boils very irregularly (bumps). Geyser phenomena occur because of great hydrostatic pressure due to the water.

233. Relation between Boiling-point and Altitude. Since the boiling-point is dependent on atmospheric pressure, a

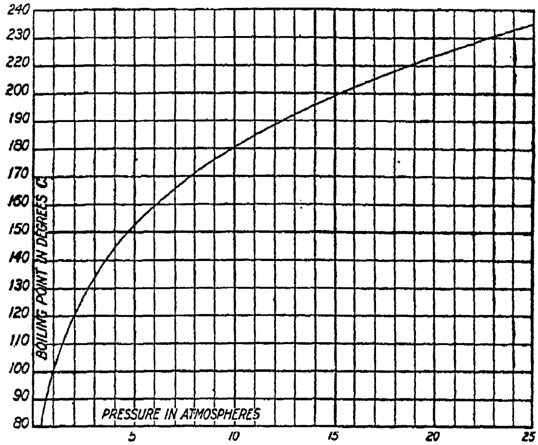


FIG. 247.—Curve showing the relation between the pressure and the boiling-point of water.

liquid in an open vessel will boil at a lower temperature as the elevation above the sea-level increases. This decrease is roughly 1° C. for an increase in elevation of 239 metres (= 961 feet). The boiling-point of water at the summit of Mont Blanc (15,781 feet) is about 85° C., and at Quito (9,520 feet), the highest city in the world, it is 90° C.

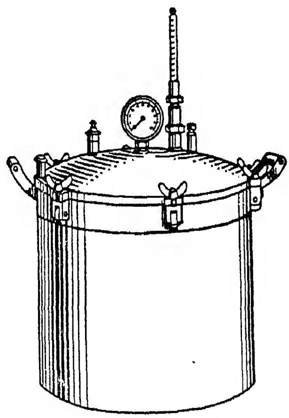


FIG. 248.—A pressure cooker. The clamped lid retains the steam (until the safety valve opens). This increases the pressure and raises the boiling-point.

In such high altitudes the boiling-point of water is below the temperature required for cooking many kinds of food, and artificial means of raising the temperature have to be resorted to, such as cooking in brine instead of pure water, or using closed vessels with safety devices to prevent explosions (Fig. 248). Sometimes longer boiling is all that is required.*

*Eggs can be cooked by boiling in an open vessel on Pike's Peak, 14,108 feet high.

BOILING POINTS OF SOME SUBSTANCES (At Standard Pressure)

Substance	B.P.	Substance	B.P.	Substance	B.P.
Alcohol (Ethyl).	78° C.	Ether........	35° C.	Liquid Air...	−191° C.
Alcohol (Methyl)....	66	Hydrochloric Acid.......	110	Mercury....	357
Benzine.......	80	Nitric Acid...	86	Sulphur.....	444
Chloroform....	61	Sulphuric Acid	338	Turpentine (Oil)......	159

234. Distillation. Distillation is a process of vaporization and condensation maintained usually for the purpose of freeing a liquid from dissolved solids, or for separating the constituents of a mixture of liquids. Fig. 249 shows a simple form of distillation apparatus. The liquid to be distilled is evaporated in the flask A, and the product of the condensation of the vapour is collected in the receiver B. The pipe connecting A and B is kept cold by cold water made to circulate in the jacket which surrounds it. The separation of liquids by distillation depends on the principle that different liquids have different boiling-points, and consequently are vaporized and can be collected in a regular order. For example, when crude petroleum is heated in a still, the dissolved gaseous hydrocarbons are driven off first; then follow the lighter oils, naphtha, gasoline and benzine; in turn come the kerosene or burning oils; and later the heavier gas and fuel oils, etc. To obtain a quantity of any one constituent of a mixture in a relatively pure state, it is necessary to resort to *fractional distillation*. The fraction of the distillate which is known to contain most of the liquid desired is redistilled, and a fraction of the distillate again taken for further distillation, and so on.

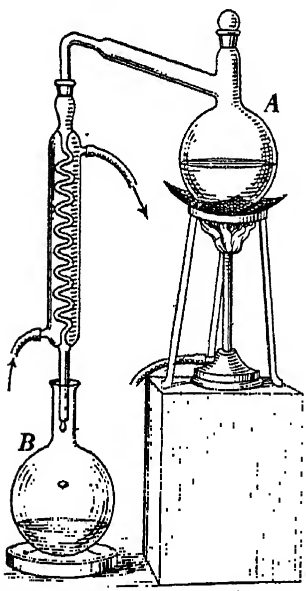


FIG. 249.—Distillation apparatus.

Experiment. Make up a brine solution and colour it with some potassium permanganate. Place it in the flask A and examine and taste the distillate in B. Conclusion?

QUESTIONS AND PROBLEMS

1. The singing of a tea-kettle just before boiling is said to be due to the collapse of the first bubbles formed in their upward motion through the water. Explain the cause of the collapse of these bubbles.

2. When water is boiling in a deep vessel, the bubbles of vapour are observed to increase in size as they approach the surface of the water. Give a reason for this.

3. Why is it necessary to take into account the pressure of the air in fixing the boiling-point of a thermometer?

235. Heat of Vaporization. When we apply heat to a beaker of water, the temperature rises steadily until the boiling-point is reached. Then the temperature remains constant until all of the water has boiled away.

Whenever a given mass of a liquid changes into a vapour, a definite amount of heat is absorbed, which does not produce a change in temperature. Thus in the process of vaporization a certain amount of energy ceases to exist as heat, and (in a manner similar to fusion) becomes potential energy in the vapour. In accordance with the law of Conservation of Energy, all heat which thus disappears is recovered when the vapour condenses.

The amount of heat required to change one gram of any liquid into vapour without changing the temperature is called the **heat of vaporization**, or sometimes the **latent heat of vaporization.** For example, the heat of vaporization of water is 540 calories, by which we mean that, when water is boiling under the standard atmospheric pressure (76 cm. of mercury), 540 calories of heat are required to vaporize one gram without change of temperature.

236. Determination of Heat of Vaporization. The heat of vaporization of water may be determined as follows: By means of apparatus arranged as shown in Fig. 250, pass steam for a few minutes into a quantity of water in a vessel C. For this vessel a metal calorimeter is preferable to a beaker

(see § 215). Take the weight and the temperature of the water before and after the steam is conveyed into it, and find the increase in mass and temperature due to the condensation of the steam.

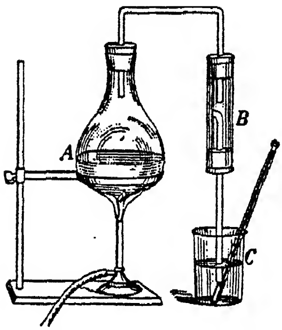


Fig. 250.—Determination of heat of vaporization of water. *A*, flask to contain water; *B*, trap to catch water condensed in the tube; *C*, vessel with known mass of water.

Suppose the mass of water in *C* at first to be 120 grams (including the water equivalent of the calorimeter) and the mass of steam condensed to be 5 grams; and suppose the initial and final temperatures of the water to be 10° C. and 35° C. respectively.

Make the calculation thus:

Heat gained by the original 120 gm. water = 120 (35 − 10) = 3000 cal.

This heat comes from two sources,

(*a*) The heat received from the condensation of 5 grams of steam at 100° C. to water at 100° C.

(*b*) The heat received from the fall in temperature of 5 grams of water from 100° C. to 35° C. = 5 (100 − 35) = 325 cal.

Hence, the heat set free by the condensation of 5 grams of steam
= 3000 − 325 = 2675 cal.

And the heat set free in the condensation of 1 gram of steam
= 2675 ÷ 5 = 535 cal.

This result is about one per cent. too low. The value now accepted for the heat of vaporization of water is 540 calories per gram.

Heat of Vaporization of Some Liquids

B.P., Boiling-point; H. of V., Heat of Vaporization.

Substance	B.P.	H.of V.	Substance	B.P.	H.of V.
Acetic Acid.....	118° C.	85	Chloroform......	61° C.	58
Alcohol (Ethyl)..	78	205	Ether...........	35	90
Alcohol (Methyl)	66	267	Liquid Air.......	−191	55
Ammonia.......	−33·5	327	Sulphur Dioxide..	−10	96
Benzine........	80	93	Turpentine (oil)..	159	74
Carbon Disulph.	46	84	Water...........	100	540

QUESTIONS AND PROBLEMS

1. The steam in a radiator and the water which is condensed from it may both be at the same temperature. Explain how the room has been warmed.

2. Why does not a mass of liquid air in an open vessel immediately change into gas when brought into a room at the ordinary temperature?

3. A vertical cylinder is one-third filled with water, and immediately above the water is fitted an air-tight piston. The piston is then drawn out nearly to the end of the cylinder. If no heat passes in or out through the piston, or the walls of the cylinder, how does the temperature of the water change? Explain.

4. Why is a pan of water often put into an oven where custards are being baked? Explain.

5. What limits the elevation of the temperature inside a loaf of bread or a piece of meat that is being baked in an oven?

6. How much heat will be required to vaporize 37 gm. of water?

7. How many calories of heat are set free in the condensation of 340 gm. of steam at 100° C. into water at 100° C.?

8. How much heat is required to raise 45 gm. of water from 15° C. to the boiling-point and convert it into steam?

9. How much heat is given up in the change of 365 gm. of steam at 100° to water at 4° C.?

10. If 34·5 gm. of steam at 100° C. are conveyed into 500 gm. of water at 20° C., the resulting temperature is 60° C. Find the heat of vaporization of water.

11. In an experiment 10 gm. of steam at 100° C. were passed into 200 gm. of water, originally at 10° C. The final temperature was 40° C. Find the heat of vaporization of water.

12. How many grams of steam at 100° C. will be required to raise the temperature of 300 gm. of water from 20° C. to 40° C.?

13. How many grams of steam at 100° C. will just melt 25 gm. of ice at 0° C.?

14. What is the resulting temperature when 45 gm. of steam at 100° C. are passed into 600 gm. of ice-cold water?

15. How much heat is necessary to change 30 gm. of ice at − 15° C. to steam at 100° C.?

16. How many grams of steam at 100° C. must be passed into 200 gm. of ice-cold water to raise it to the boiling-point? What will happen if more steam than this is passed in?

CHAPTER XXXVIII

ARTIFICIAL REFRIGERATION

237. Cold by Evaporation. In order to change a liquid into vapour, heat is always required. Water placed over a flame is turned into vapour, the heat required being supplied by the flame. If a little ether is poured on the palm of the hand, it vaporizes at once. Here the heat to produce vaporization is supplied by the hand, which therefore feels cold. For a similar reason wet garments are cold, especially if drying rapidly on a windy day.

But it is sometimes possible to produce vaporization without supplying heat from an outside source. In this case the heat comes from the liquid itself, which must, therefore, fall in temperature. Indeed, it is possible, by producing evaporation, to lower the temperature of water so much that the water will actually freeze. This is well shown in Leslie's experiment.* A small quantity of cold water in a watch glass is inclosed in the receiver of an air-pump over or near a dish of strong sulphuric acid (Fig. 251). The air is then exhausted from the receiver. When the pressure is reduced sufficiently, the water begins to boil, and as the vapour is removed from the receiver, partly by being carried off with the air by the pump, and partly by absorption into the sulphuric acid, the process continues until the water is frozen. The water actually boils and freezes at the same time.

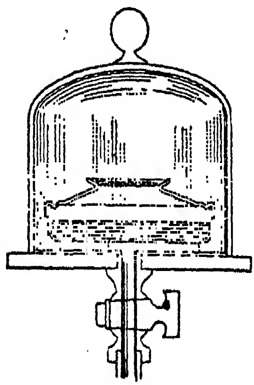


FIG. 251.—Leslie's experiment; freezing water by its own evaporation.

*Sir John Leslie (1776-1832) Scottish mathematician and physicist at the University of Edinburgh.

238. Solid Carbon Dioxide—"Dry Ice". Similar results are shown in a more striking manner by the freezing of carbon dioxide by evaporation from the liquid form. If the liquid carbon dioxide (contained in a strong steel cylinder) is allowed to escape into a bag attached to the outlet pipe of the cylinder (Fig. 252), it will be frozen into snowy crystals by the intense cold produced in the rapid evaporation of the liquid. Its temperature is —112° F. or —80° C.

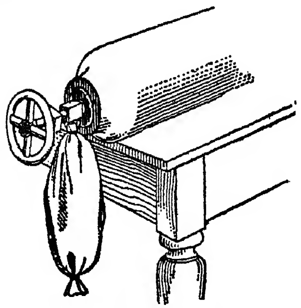


Fig. 252. — Freezing of carbon dioxide by evaporation from the liquid form.

If this carbon dioxide snow is moulded into blocks under a pressure of from 500 to 800 pounds per square inch, it becomes a hard solid called "dry ice" because it vaporizes slowly without passing through an intermediate liquid state. Because of this fact ice cream may be packed in paper boxes surrounded by dry ice and sent considerable distances by mail. Its heat of vaporization from solid to gas is 134 calories per gram, which makes solid carbon dioxide much more effective than ice as a cooling agent.

239. Applications of Cooling by Vaporization. Our chief source of "artificial cold" is vaporization. The applications are numerous and varied. Fever patients are sponged with volatile liquids to reduce temperature. Ether sprays are used to freeze material for microscopic sections and as a local anesthetic in minor surgical operations. Vaporization is also utilized in making artificial ice, in cooling cold-storage buildings, and in freezing shifting quicksands for engineering purposes. Many theatres, stores and even private dwellings are now cooled artificially in summer by this means. The liquid most commonly used for the latter purposes is ammonia liquefied by pressure. This is suitable because the gas liquefies at ordinary temperature under relatively moderate

pressure (about 10 atmospheres), and it absorbs a great amount of heat in vaporization.

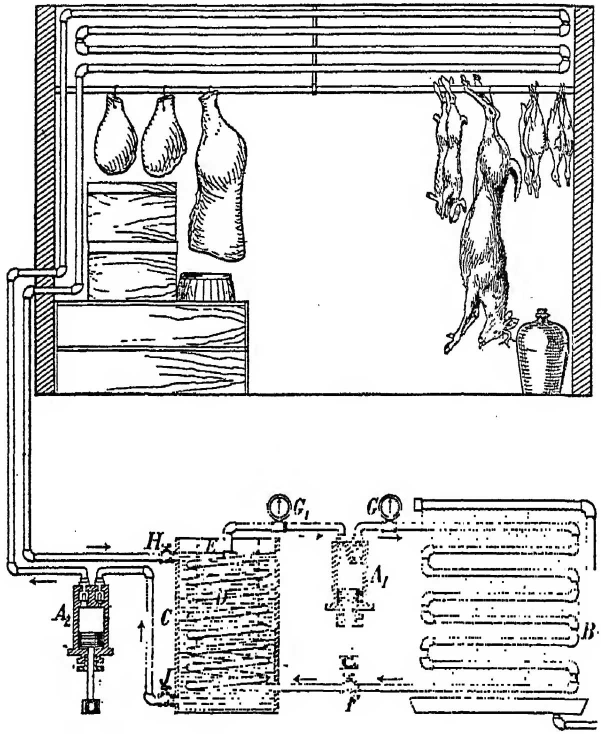


FIG. 253.—Cold-storage plant.

Figure 253 shows the essential parts of a refrigeration plant. The principle involved is the same in nearly every method of cooling. A liquid is changed to a vapour and the heat absorbed in bringing about this change produces the cooling effect. The substance to be used as a refrigerant should be changed easily from gas to liquid and *vice versa.* Such substances are ammonia, sulphur dioxide, methyl chloride, ethyl chloride and carbon dioxide. The first named is usually employed in commercial plants.

When the piston in A_1 descends, the ammonia gas is pumped into the condensing coils B and is liquefied there by pressure, the heat in the ammonia produced by the condensation being carried off by cold water running down the outside of the coils. The liquid ammonia es-

capes slowly through a regulating valve F into the low-pressure coil D, where it evaporates, and in so doing takes heat from the brine in C which surrounds the low-pressure coils, reducing its temperature to about 16° F.

As the piston rises the vapour from D is drawn into the pump cylinder and is ready to start its journey through the machine again when the piston descends. The same ammonia is thus used over and over again.

The cold brine in C is pumped by means of the pump A_2 through pipes distributed about the chambers to be cooled. To make ice the water may be placed in cans and submerged in the brine in C.

240. Household Refrigerator. Mechanical refrigerators for ordinary household purposes are now in very common use. Fig. 254 shows the main parts of a refrigerator.

The electric motor drives the compressor, and the refrigerant, usually methyl chloride gas, is pumped into the condenser coils where it is cooled and condensed by air blown over the coils by means of a fan attached to the motor. The liquid thus formed is driven over into the liquid receiver. From here it passes up a tube to the float valve which is closed when there is no liquid in the float chamber. As liquid is forced into the float chamber it raises the float and opens the valve. Liquid now passes into the cooling unit coils where it evaporates because of the low pressure existing in these coils. Heat required for the evaporation of the liquid is taken from surrounding objects in the refrigerator. The food chamber is completely surrounded by a layer of insulation 2 to 4 inches thick to prevent the entrance of heat from outside. The gas returns to the compressor through the suction pipe because of the low pressure produced below the piston during its up-stroke. Trays of water for making ice cubes are placed on shelves inside the cooling unit. The temperature in the food chamber should lie between 40° F and 50° F. When it rises above this a thermostat (not shown) which is attached to the cooling unit closes an electric circuit and starts the motor which drives the compressor. When the temperature has been lowered sufficiently the thermostatic control automatically stops the motor. Thus the operation is entirely automatic.

241. Condensation—Critical Temperature. A vapour in a condition of saturation is condensed if its temperature is lowered or its pressure is increased. At this point an interesting question arises. Can an unsaturated vapour at any given condition of temperature be reduced to a liquid by increase of pressure alone? The question has been answered experimentally. It has been found that for every vapour there is a temperature above which pressure alone, however great, cannot

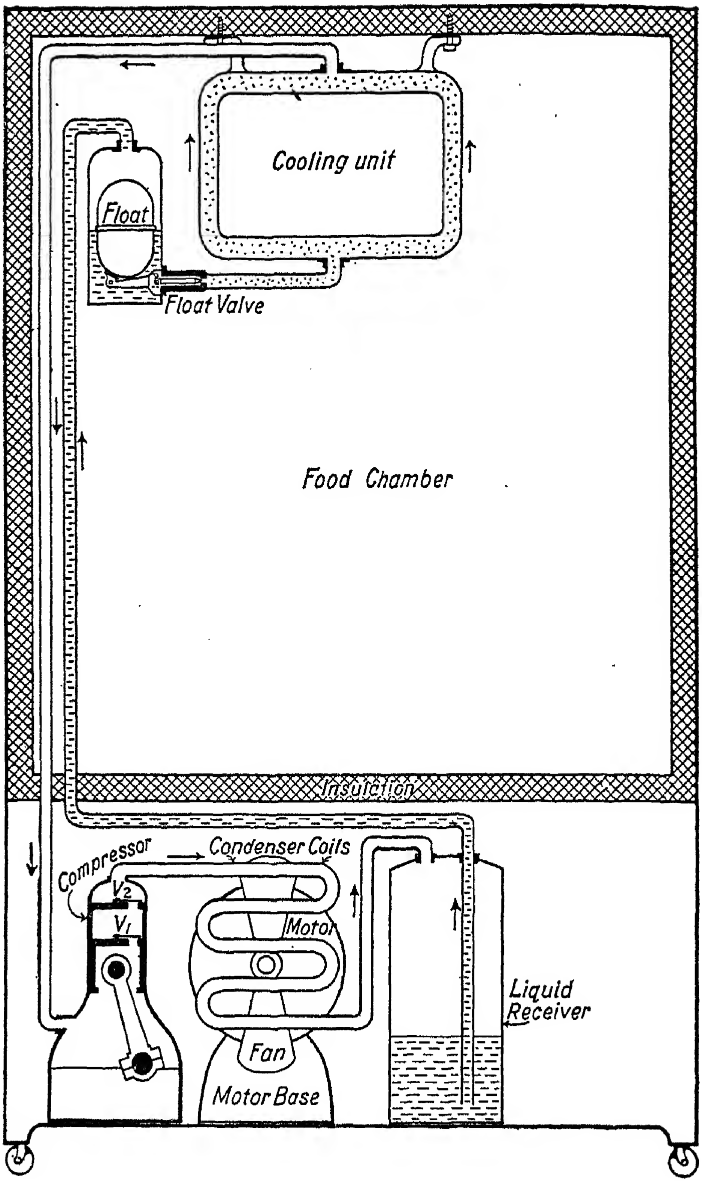


FIG. 254.—Diagram of a Household Refrigerator.

produce condensation. This temperature is known as the **critical temperature**, and the pressure necessary to produce condensation at this temperature is called the **critical pressure**. For example, Andrews,* to whom we owe an exhaustive study of the subject, found that to reduce carbon dioxide to a liquid the temperature must be lowered to at least 30·92° C., and that above that temperature no amount of pressure would convert it into liquid form.

The critical temperature of water, alcohol, ammonia, and carbon dioxide are above the average temperature of the air, while those of the gases oxygen, hydrogen and air are much below it. The critical temperature of water is 374° C. and of air − 140° C.

Below the critical temperature a further lowering of the temperature lessens the pressure necessary to condensation. For example, a pressure of 73 atmospheres is necessary to condense carbon dioxide at the critical temperature, but 60 atmospheres is sufficient at a temperature of 21·5° and 40 atmospheres at a temperature of 13·1°. Again, a pressure of 218 atmospheres is necessary to condense steam at the critical temperature (374° C.); at 100° C. it condenses under a pressure of one atmosphere.

QUESTIONS AND PROBLEMS

1. Why does sprinkling the floor have a cooling effect on the air of the room? An electric fan would increase the cooling. Why?

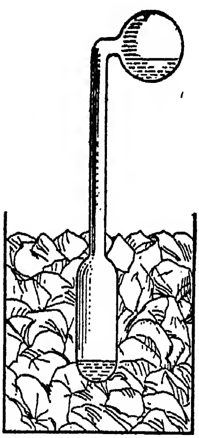


Fig. 255.—Cryophorus.

2. On opening a window a current of air cools you but does not lower the mercury in a thermometer on which it falls. Why not?

3. Under what conditions will "fanning" cool the face?

4. In eastern countries and at high elevations water is poured into porous earthenware jars and placed in a draught of air to cool. Explain the cause of cooling.

5. A tube having a bulb at each end has some water in one of its bulbs, the remaining space containing nothing but water-vapour. The empty bulb is surrounded by a freezing mixture (Fig. 255), and after a time it is found that the water in the other (upper) bulb is frozen. Explain. (Such a tube is called a *cryophorus*, which means *frost-carrier*.)

6. A little alcohol sprinkled on the bulb of a thermometer causes an immediate lowering of the temperature indicated by the thermometer,

*Thomas Andrews (1813-1885) Professor of Chemistry, Queen's College, Belfast, 1845-1879

even though the thermometer shows no change in temperature when the bulb is immersed in the alcohol. Explain.

7. A beaker is placed on a board (say the lid of a chalk box), and a small amount of water placed on the board under the beaker. Ether is poured into the beaker and allowed to fill the lower part of it. Now if air is forced into the ether by means of an atomizer bulb and a glass tube and made to bubble up through it freely for a time, the beaker will be frozen to the board. Try the experiment and explain the result.

8. The boiling-point of a solution of common salt is higher than that of pure water; the freezing-point of the solution is lower than that of pure water. Use the molecular theory to explain these facts.

9. A thermometer placed in the steam above a boiling solution will indicate the boiling-point of water and not that of the solution. Explain.

10. Is there a perfect vacuum in the space above the mercury in a barometer? How would the presence of a little water in the mercury affect the height of the barometer? Under what conditions of temperature would the effect be most noticeable?

CHAPTER XXXIX

MOISTURE IN THE ATMOSPHERE

242. Condensation of Water-vapour of the Air — Dew-point. Evaporation is constantly taking place from water at the surface of the earth, and consequently the atmosphere always contains more or less water-vapour. This vapour will be on the point of condensation when its pressure approaches the saturation pressure. Now, since this pressure varies with the temperature, the nearness to saturation at any given time will depend on the temperature as well as upon the amount of vapour present per unit volume. It has been found that the amount of vapour which a given space will contain rises rapidly with the temperature. Thus a given space will hold more than three times as much vapour at 30° C. as at 10° C., and nearly five times as much at 60° C. as at 30° C.

Suppose the amount of vapour in a given space to remain constant and let the temperature be lowered gradually; at length a temperature will be reached at which condensation begins. That is the dew-point, which may be defined as **that temperature at which the moisture present in the air is sufficient to saturate it.**

It is usual to speak of the air as containing the vapour, but that is somewhat misleading. The vapour exists along with, and independent of, the air. We can conceive of the air being removed from a certain space (say, a cubic metre) and the vapour still remaining there.

243. Dew-point Hygrometer. The dew-point may be determined experimentally by Regnault's hygrometer* illus-

*Hygrometer, from two Greek words meaning *moisture* and *measure*.

trated in Fig. 256. In it are two glass tubes the lower portions of which are covered with polished metal. A thermometer is inserted through the cork in each. Pour ether into the vessel fitted with the atomizer bulb and force air through it. This agitation of the ether makes it evaporate rapidly, and thus the temperature of the vessel is lowered. Note the temperature at which the polished surface surrounding the ether becomes dimmed with dew. Cease forcing the air and note the temperature at which the moisture disappears. The mean of the two temperatures is taken as the dew-point.

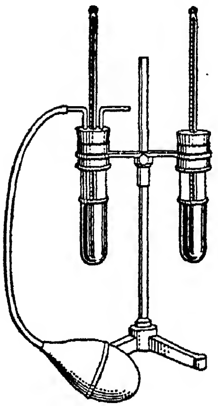


FIG. 256.—Determination of the dew-point.

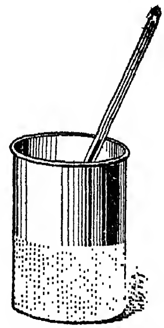


FIG. 257.—A polished metal cup for finding the dew-point.

The second vessel enables the observer, by comparison, to determine more readily the exact moment when condensation begins. The thermometer in this vessel gives the temperature of the air in the room at the time of the experiment.

The dew-point may also be found by using the simple apparatus shown in Fig. 257. The polished metal cup is half-filled with water, and snow or small pieces of ice are dropped in at intervals. The water is kept well stirred and the temperature at which the dew appears is noted. The temperature at which the dew disappears should also be noted and the average taken as before.

244. Relative Humidity. The term **humidity, or relative humidity,** is used to denote **the ratio of the mass of water-vapour present in the air, to the mass required for saturation at the same temperature.** The air is said to be very dry when the ratio is low, and damp when it is high. These

terms, it should be observed, have reference, not to the absolute amount of vapour present, but to the relative degree of saturation at the given temperature. At the present moment the air outside may be raw and damp, but after having been forced by a fan over a series of steam-heated coils, it appears in the laboratory comparatively dry. It is not to be inferred that the air has lost any of its vapour; but rather that in being heated it has acquired the capacity of taking up more.

The relative humidity is usually expressed as a percentage of the maximum amount of vapour possible at the temperature. For example, when the air contains but one-half of the amount of water-vapour necessary for saturation, its humidity is 50 per cent.

245. Chemical Hygrometer. This instrument (Fig. 258) provides a direct method for determining the mass of water-vapour present in a given volume of air. It requires very careful handling but it obtains results on which the use of other hydrometers depend.

A is a large bottle of at least 10 litres capacity, which is nearly full of water at the beginning of the experiment. By opening the tap *B* air can be drawn through the U-tubes *C*, *D*, *E*, in which is placed calcium chloride or some other substance which absorbs water-vapour readily. The bottle *F* contains strong sulphuric acid, which prevents any water-vapour from passing from *A* to the drying tubes *C*, *D*, *E*. These tubes are weighed before the experiment and again after a measured volume of water has escaped by the tap *B*. The average temperature of the air during the experiment is obtained by reading the thermometers *G* and *H*.

Let the volume of the water be 10 litres and the increase in the weight of the tubes be 0·05 gm. Then 1 litre of air under the given conditions contains 0·005 gm. of water-vapour.

We must now find the weight of water-vapour which would saturate this volume of air under the same conditions of temperature. This can be obtained by making the air first pass through tubes containing sponge or wool soaked in water before it comes to the drying tubes. Let the amount of vapour present in 1 litre of saturated air be 0·020 gm. Then the relative humidity [illegible] $\times 100 = 25\%$.

The following table gives the mass of water-vapour present in 1 cubic metre (= 1000 litres) of saturated air at different temperatures.

Temp. Centigrade.	−10°	−5°	0°	5°	10°	15°	20°	25°	30°
Mass in grams....	2·1	3·5	4·9	6·8	9·4	12·8	17·2	22·9	30·[illegible]

Exercise. Using this table, plot a curve (similar to that in Fig. 247) in which horizontal distances represent temperatures and vertical distances represent masses of water-vapour; and from the curve estimate the mass of water-vapour present in 1 cu. metre of saturated air at $-2\frac{1}{2}°$, $7\frac{1}{2}°$ and $27\frac{1}{2}°$ C.

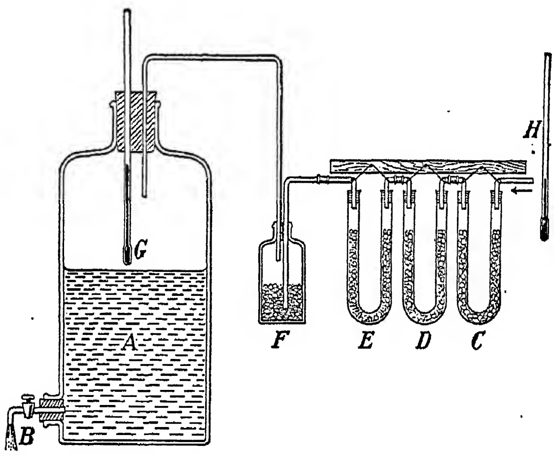


FIG. 258.—A chemical hygrometer for actually weighing the water-vapour present in a given volume of air.

246. Relative Humidity from the Dew-point. Having once obtained the table just given, the relative humidity is easily determined by a calculation from tne dew-point. Take a particular example. Suppose the dew-point to be 10° C. while the temperature of the air in the room is 20° C. From the table we learn that air saturated with water-vapour at 10° C. contains 9·4 gm. per cubic metre, and at 20° C. it contains 17·2 gm. per cubic metre. Then since 1 cubic metre actually contains at 20° C. just the amount of vapour

necessary for saturation at 10° C. the relative humidity $= \frac{9.4}{17.2}$ or 54·6%.

247. Wet-and-Dry-Bulb Hygrometer. This instrument consists of two similar thermometers mounted on the same stand (Fig. 259). The bulb of one of the thermometers is covered with muslin kept moist by a wick immersed in a vessel of water. Evaporation from the wet bulb lowers its temperature, and since the ratio of evaporation varies with the dryness of the atmosphere, it is evident that the differences in the readings of the thermometers may be used as an indirect means of estimating the relative humidity of the atmosphere. The percentages are given in tables prepared by comparison with results determined from dew-point calculations.

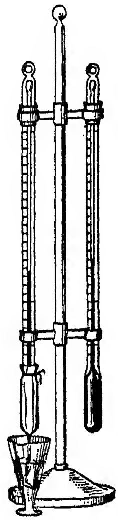


Fig. 259.—Wet-and-dry-bulb hygrometer.

For accurate results the hygrometer should be placed in a brisk current of air.

Example. Suppose the dry thermometer reads 71 and the wet 62. Find 71 on the left-hand side (of the table below) and take the line running to the right from it. Then find 62 at the top and take the column running down from it. The number where these two meet is 60, and that is the relative humidity.

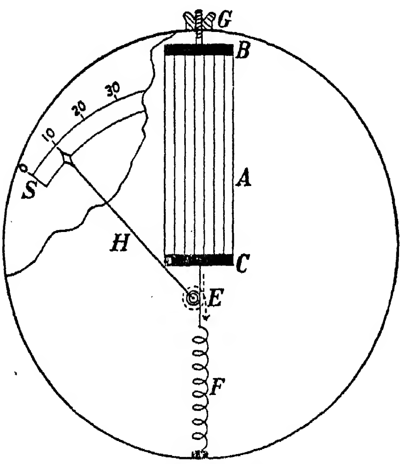


Fig. 260.—A direct-reading hygrometer.

248. Direct-Reading Hygrometers. It requires considerable time and manipulation of apparatus to obtain the relative humidity by the use of the hygrometers so far described. The direct-reading instrument shown in Fig. 260 enables a person to read the humidity at once by noting the position of a pointer on a scale.

TABLE GIVING RELATIVE HUMIDITY

Reading of Dry Thermometer (Fahr.)	Reading of Wet Thermometer (Fahr.)																	
	70	**69**	**68**	**67**	**66**	**65**	**64**	**63**	**62**	**61**	**60**	**59**	**58**	**57**	**56**	**55**	**54**	**53**
80	61	57	54	51	47	44	41	38										
79	63	60	57	54	50	47	44	41	37									
78	67	64	60	57	53	50	46	43	40	37								
77	71	67	63	60	56	52	49	46	42	39	36							
76	74	70	67	63	59	55	52	48	45	42	38	35						
75	78	74	70	66	63	59	55	51	48	44	40	38	34					
74	82	78	74	70	66	62	58	54	51	47	43	40	37	34				
73	86	82	78	73	69	65	61	58	54	50	46	43	40	36	33			
72	91	86	82	78	73	69	65	61	57	53	49	46	42	39	35	32		
71	95	90	86	82	77	73	69	64	60	56	53	49	45	41	38	34	31	
70		95	90	86	81	77	72	68	64	60	56	52	48	44	40	37	33	30
69			95	90	86	81	77	72	68	64	59	55	51	47	44	40	36	32
68				95	90	85	81	76	72	67	63	59	55	51	47	43	39	35
67					95	90	85	80	76	71	67	62	58	54	50	46	42	38
66						95	90	85	80	76	71	66	62	58	53	49	45	41
65							95	90	85	80	75	70	66	62	57	53	48	44
64								95	90	85	79	75	70	66	61	56	52	48
63									95	90	84	79	74	70	65	60	56	51
62										94	89	84	79	74	69	64	60	55
61											94	89	84	79	74	68	64	59
60												94	89	84	78	73	68	63

A is a bundle of hairs or specially prepared parchment which possesses the property of readily absorbing water-vapour from the air. The ends are fastened to bars *B* and *C*. *B* has a small threaded bolt fastened to it which passes through the case so that adjustment may be made by turning the nut *G*. Connected to the lower bar *C* is a light chain or cord which passes around the pulley *E* and has its lower end attached to the spring *F*. A pointer *H* is attached to the axis of the pulley and moves over the scale *S* which gives the relative humidity as a per cent.

The action is simple. The greater the relative humidity, the greater is the amount of water-vapour absorbed by *A* and the more easily is it stretched by the spring *F*. Consequently the cord turns the pulley clockwise and the pointer moves to the right. When the humidity drops *A* loses moisture and contracts making the pointer move to the left.

The instrument must be checked with some other form of hygrometer and adjusted periodically.

249. Relation of Humidity to Health. Humidity has an important relation to health and comfort. When the relative humidity is high, a hot day becomes oppressive because the dampness of the atmosphere interferes with free evaporation from the body. On the other hand, when the air becomes too dry, the amount of this evaporation is too great. This condition very frequently prevails in winter in houses artificially heated. Under normal conditions the relative humidity should be from 50 to 60 per cent, but in winter in Ontario it is usually not more than 30 per cent. in most buildings. As a result the evaporation from the skin and respiratory passages takes place too rapidly.

This abnormal dryness of the air is probably one reason for the prevalence of respiratory infections (colds, etc.) during the winter months. This matter is referred to again in § 266.

250. Fog and Clouds. If the air is chilled below the temperature for saturation, vapour condenses about dust particles suspended in the air. If this condensation takes place in the strata of air immediately above the surface of the earth, we have a **fog**; if in a higher region, a **cloud**. The cooling necessary for fog formation is due to the chilling effects of cold masses at the surface of the earth; in the upper region, a cloud is formed when a stratum of warm moist air has its temperature lowered by its own expansion under reduced pressure. It would appear from recent investigations that under all conditions dust particles are necessary as nuclei for the formation of cloud globules.

The effect of dust particles in producing fog and clouds can be shown in a striking manner as follows:

A large bottle *A* is connected to an air-pump and to a smaller bottle *B* (Fig. 261). A little water is placed in *B* to ensure that the air within it is saturated with water-vapour. The pinch-cocks *C* and *E* are

closed while the air is exhausted from A. D is then closed and C opened. The sudden expansion of the air in B cools it sufficiently to produce a fog. If now a little smoke from burning paper is introduced into B through E and the experiment is repeated, the fog is many times as dense.

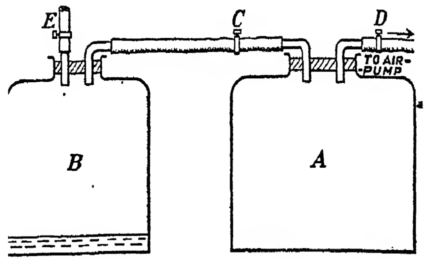


FIG. 261.—To illustrate the production of fog.

251. Dew and Frost; Rain, Snow and Hail. On a warm summer day drops of water collect on the surface of a pitcher containing ice-water, because the air in immediate contact with the pitcher is chilled below the dew-point. This action is typical of what goes on on a large scale in the deposition of **dew.** After sunset, especially when the sky is clear, small bodies at the earth's surface, such as stones, blades of grass, leaves, cobwebs, and the like, cool more rapidly than the surrounding air. If their temperature falls below the temperature of saturation, dew is deposited on them from the condensation of the vapour in the films of air which envelop them. If the dew-point is below the freezing-point, the moisture is deposited as frost.

The cloud globules gravitate slowly towards the earth. If they meet with conditions favourable to vaporization, they change to vapour again, but if with conditions favourable to condensation, they increase in size, unite, and fall as **rain.**

When the condensation in the upper air takes place at a temperature below the freezing-point, the moisture crystallizes in **snow-flakes.** At low temperatures, also, vapour becomes transformed into ice pellets and descends as **hail.** The hailstones usually contain a core of closely packed snow crystals. The exact conditions under which they are formed are not yet fully understood but probably they arise from the action

of violent air currents which carry the condensed vapour up and down through alternate regions of snow and rain.

QUESTIONS AND PROBLEMS

1. As exhaustion of air proceeds, a cloud is frequently seen in the receiver of an air-pump. Explain.

2. Why can one "see his breath" on a cold day?

3. Dew does not usually form on a pitcher of ice-water standing in a room on a cold winter day. Explain.

4. On some days a locomotive leaves a long white cloud behind it and on other days only a short one. What causes the difference? Also, why does the cloud form and why does it disappear?

5. A saucer containing water is left to evaporate on a window-sill. Explain what atmospheric conditions will favour or retard the disappearance of the water.

6. On drawing 30 litres of atmospheric air through a series of drying tubes, the weight of the drying tubes increases by 0·288 gm. The temperature is 20° C. What is the relative humidity and what the dew-point?

7. Find from the table in § 244 the relative humidity corresponding to the following conditions:

   (*a*) Temp. of atmosphere 10° C. dew-point 5° C.
   (*b*) Temp. of atmosphere 15° C. dew-point 7½° C.
   (*c*) Temp. of atmosphere 25° C. dew-point 15° C.

8. Why does a morning fog frequently disappear with increased strength of the sun's rays?

CHAPTER XL

TRANSFERENCE OF HEAT: CONDUCTION AND CONVECTION

252. Conduction of Heat. The handle of a silver spoon becomes warmed when the bowl is allowed to stand in a cup of hot liquid; the bare end of a glass stirrer, under similar conditions, remains practically unchanged in temperature. Heat creeps along an iron poker when one end is thrust into the fire; while a wooden rod conveys no noticeable heat to the hand.

The transference of heat from hotter to colder parts of the same body, or from a hot body to a colder one in contact with it, is called **conduction**, when the transmission takes place, as in these instances, without any perceptible motion of the parts of the bodies concerned.

The motion of the molecules of a solid is supposed to be a sort of oscillation about their mean positions. When the end of the rod is heated the molecules there are thrown into more rapid vibration. These molecules bump into their neighbours and set them vibrating more rapidly. In this manner the heating effect is transmitted along the rod.

253. Conducting Powers of Solids. The above examples show clearly that solids differ widely in their power to conduct heat. The behaviour in silver and iron is typical of the metals; as compared with non-metals, they are good conductors. Organic fibres, such as wool, silk, wood, and the like, are poor conductors.

The metals, however, differ widely among themselves in conductivity. This may be shown experimentally as follows:

Experiments. 1. Twist two or more similar wires of different metals—say copper, iron, German silver—together at the ends and mount them as shown in Fig. 262. By means of drops of wax attach small nails or other small objects at equal intervals along the wires. Heat the twisted ends. The progress of the heat along the wires will be indicated by the melting of the wax and the dropping of the nails. When the line of separation between the melted and unmelted drops of wax ceases to move along the wire, it will be found that the copper has melted wax at the greatest distance from the source of heat, the iron comes next in order, and the German silver last.

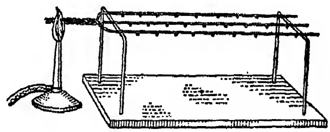


Fig. 262.—Difference in conductivity of metals.

2. The apparatus shown in Fig. 263 is capable of more accurate results. In it rods of six different metals are inserted into the lower side of a pipe through which steam may be passed. The rods are coated with a special red paint which becomes quite dark when heated, and the greater the conductivity of the rod the farther along it will this darkening take place. Steam is passed continually through the pipe until there is no further change in the colours, or the rods have reached a "steady state." Then the lengths on the rods through which the paint has changed colour are measured, and the conductivities are proportional to the squares of these lengths. If we take the conductivity of copper as 100, the other metals will have their relative values.

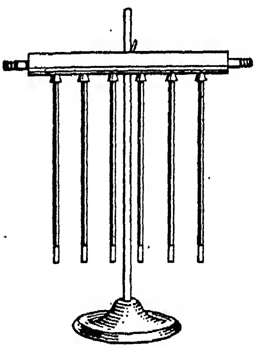


Fig. 263.—The paint on the rods changes colour as the heat travels along them.

The following table gives the relative conductivities of some of the more commonly used metals referred to copper as 100.

Relative Conductivities of Metals

Copper	100	Iron (wrought)	16	Platinum	8
Aluminium	52	Lead	9	Silver	110
Brass	28	Magnesium	41	Tin	17
Gold	77	Mercury	1·6	Zinc	29

254. Conduction in Liquids. If we except mercury and molten metals, liquids are poor conductors of heat. For example, we may boil the upper layers of water held in a test-tube over a burner (Fig. 264) without perceptibly heating the water at the bottom of the tube.

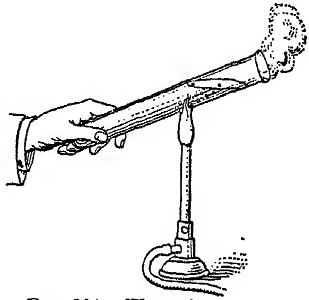


FIG. 264.—Water is a poor conductor of heat.

The poor conductivity of water is also strikingly shown in the following experiment:

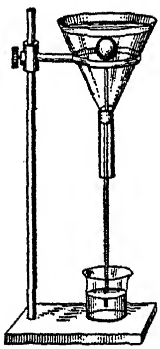


FIG. 265.—Illustration of the non-conductivity of water.

Pass the stem of a Galileo air-thermometer (§ 192) through a perforated cork inserted into a funnel as shown in Fig. 265. Then cover the bulb of the thermometer to a depth of about ½ cm. with water. Now pour a spoonful of ether on the surface of the water and set fire to it. The index of the thermometer shows that little, if any, heat is transmitted by the water to the bulb from the flame at the surface.

255. Conduction in Gases. Gases are extremely poor conductors of heat. The fact that a finger may be brought very close to the side of a hot stove or the flame from a Bunsen burner without injury shows that the air between transmits very little heat by conduction. Experiments on measuring the conductivity of gases are, however, difficult to perform because heat is readily transmitted in gases by other methods.

The conductivity of air is estimated to be only about $\frac{1}{17000}$ of that of copper. Many substances, such as wool, fur, down, etc., owe their poor conductivity to the fact that they are porous and contain air in their interstices. If these substances are compressed, they become better conductors.

Light, freshly fallen snow incloses within it large quantities of air, and consequently forms a warm blanket for the earth, protecting the roots of plants from intense frost. Double windows, hollow tiles and hollow walls in houses are effective as heat insulators largely on account of the inclosed volume of air.

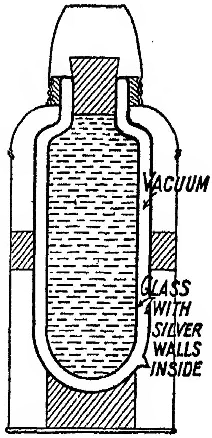


FIG. 266.—A thern bottle.

The most effective non-conductor of all is a vacuum. The familiar "thermos" bottle (invented by Sir James Dewar about 1892 for holding liquid air) consists of a glass vessel with double walls and having the air removed from the space between the walls (Fig. 266). The inner surfaces of the walls are silvered to prevent loss or gain of heat through radiation (§ 269). In such a vessel, a hot substance will remain hot and a cold one cold for a long time.

256. Importance of Conductivity. Frequently the suitability of a substance for a particular purpose depends on its ability to conduct heat. Furnaces, steam boilers, cooking utensils, etc., should be constructed from materials which are good conductors. Again, other ces are useful because they are good insulators or bad conductors. A house with double walls is warm in winter and cool in summer. Wool and fur are utilized for winter clothing because they do not allow the heat of the body to escape through them.

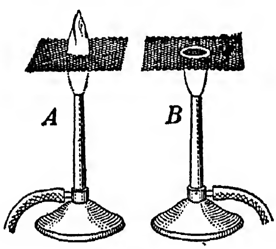


FIG. 267.—Action of metallic gauze on a gas-flame.

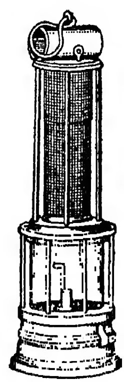


FIG. 268.—Davy safety l

The action of metallic gauze in conducting heat is interesting and may be illustrated in a simple way.

Experiment. Depress upon the flame of a Bunsen burner a piece of fine wire gauze. The flame spreads out under the gauze but does not pass through it (*B*, Fig. 267). Next, turn off the gas and hold the gauze about half an inch above the burner and apply above the gauze a lighted match (*A*, Fig. 267). The gas burns above the gauze, but not below it. The explanation is that the metal of the gauze conducts away the heat so rapidly that the gas on the side of the gauze opposite the flame is never raised to a temperature sufficiently high to light it. This principle is applied in the construction of the Davy safety lamp for miners. A jacket of wire gauze incloses the lamp, and prevents the heat of the flame from igniting any combustible gas on the outside. (Fig. 268.) If such a lamp is lighted and an unlighted Bunsen burner, from which is issuing an inflammable gas, is directed towards the flame, the gas will ignite inside the gauze but will not strike back to the burner.

257. Conductivity and Sensitiveness to Temperature. We have already remarked that our sensations sometimes deceive us regarding the relative temperatures of bodies. This is in part due to the disturbing effects of conduction. To take an example, iron and wood when exposed under the same conditions, have the same temperature; but on touching them the iron appears to be colder than the wood when the temperature is low, and hotter when it is high. These phenomena are due to the fact that the intensity of the sensation depends on the rate at which heat is transferred to or from the hand. When the temperature of the iron is low, heat from the hand is carried rapidly into its mass; when hot, the heat current flows from the iron to the hand. The wood, when cold, takes from the hand only sufficient heat to warm the film of wood in immediate contact with the hand; when hot, it parts with heat from this film only. In consequence, it never feels very cold or hot.

QUESTIONS

1. If a cylinder, half brass and half wood, be wrapped with a sheet of paper and held in the flame (Fig. 269), the paper in contact with the

wood will soon be scorched, but that in contact with the brass will not be injured. Explain.

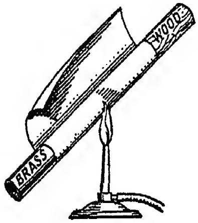


FIG. 269.

2. Why are utensils used for cooking frequently supplied with wooden handles?

3. Ice stored in ice-houses is usually packed in saw-dust. Why use saw-dust?

4. Why, in making ice-cream, is the freezing mixture placed in a wooden vessel and the cream in a metal one?

5. Water may be boiled in an ordinary paper oyster-pail over an open flame without burning the paper. Explain. Try the experiment.

6. The so-called fireless cooker consists of a wooden box lined with felt or other non-conductor. The food is heated to a high temperature and shut up in the box. Why is the cooking process continued under these conditions?

7. Two similar cylindrical rods, one of copper and the other of lead, are covered with wax, and an end of each is inserted through a cork in the side of a vessel into which boiling water is poured. At first the melting of the wax advances more rapidly along the lead rod, but after a while the melting on the copper overtakes that on the lead, and in the end it is about 3 times as far from the hot water. Account for these phenomena. Compare the conductivities of copper and lead.

8. Which would be the more dangerous to touch in a heated oven, the pan which contains a loaf of bread or the loaf itself? Why?

9. The skin is cooled much more rapidly when placed in cold water than when placed in air at the same temperature. Why?

10. Why will a moistened finger freeze instantly to a metal door latch on a very cold day, but not to the door itself?

258. Convection Currents. The water in the test-tube (§ 254) remains cold at the bottom when heated at the top. If the heat is applied at the bottom, the mass of water is quickly warmed. The explanation is that in the latter case the heat is distributed by currents set up within the fluid.

The presence of these currents is readily seen if a few crystals of potassium permanganate are dropped into a beaker

of water and the tip of a gas-flame allowed to come in contact with the bottom either at one side as in Fig. 270 or at the centre as in Fig. 271.

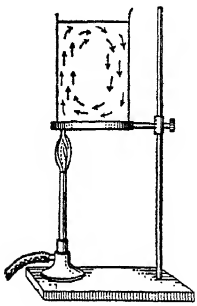


FIG. 270. — Convection currents in water heated by a gas-flame placed at one side of the bottom.

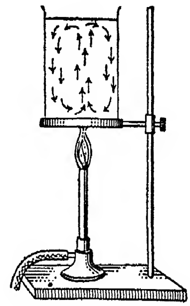


FIG. 271. — Convection currents in water heated by a gas-flame placed at the centre the bottom.

Such currents are called convection currents. They are formed whenever inequalities of temperature are maintained in the parts of a fluid. To refer to the example just cited, the portion of the water near to the gas-flame is heated and its density is reduced by expansion. The body of hot water is, therefore, buoyed up and forced to the top by the colder and heavier portions which seek the bottom.

259. Transference of Heat by Convection. The transference of heat by convection currents is to be distinguished from conduction. In conduction, the energy is passed from molecule to molecule throughout the conductor; in convection, certain portions of a fluid become heated and change position within the mass, distributing their acquired heat in their progress. The water, heated at the bottom of the beaker, rises to the top carrying its heat with it.

260. Convection Currents in Gases. Gases are very sensitive to convection currents. A heated body always causes disturbances in the air about it. The rising smoke shows the direction of the air currents above a fire. When one holds a hot iron—say a flat-iron—in a cloud of floating dust or smoke particles (Fig. 272), the air is seen to rise from the top of the iron, and to flow in from all sides at the bottom.

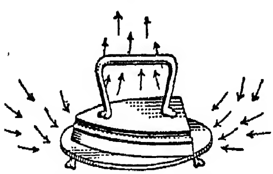


FIG. 272.—Convection currents in air about a heated flat-iron.

Experiment. Make a box fitted with a glass front and chimneys as shown in Fig. 273. Place a lighted candle under *C*, one of the chimneys, and replace the front. Light some touch paper* and hold it over *B*, the other chimney. Observe the motion of the smoke.

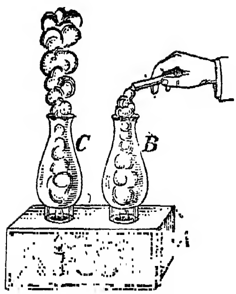


FIG. 273. — Convection currents in heated air.

261. Winds. While air currents are modified by various forces and agencies, they are all traceable to the pressure differences which result from inequalities in the temperature and other conditions of the atmosphere.

The effects of temperature differences are but manifestations, on a large scale, of convection currents, like those in the air about the heated iron. Owing to various causes the earth's surface is unequally heated by the sun. The air over the heated areas expands, and, becoming relatively lighter, is forced upward by the buoyant pressure of the colder and heavier air of the surrounding regions.

Trade winds furnish an example. These permanent air-currents are primarily due to the unequal heating of the atmosphere in the polar and the equatorial latitudes.

We have an example also, on a much smaller scale, in land and sea breezes. On account of its greater specific heat, water warms and cools much more slowly than land. For this reason the sea is frequently cooler by day and warmer by night than the surrounding land. Hence, if there are no disturbing forces, an off-sea breeze is likely to blow over the land during the day and an off-land breeze to blow out to sea at night (Fig. 274). Since the causes producing the changes in pressure are only local, these atmospheric disturbances extend but a short distance from the shore, not more than 10 or 15 miles.

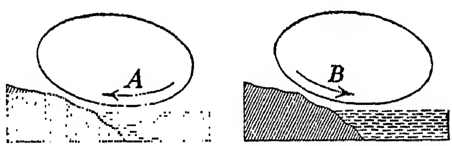


FIG. 274.—Illustration of land and sea breezes. *A*, direction of movement in sea breeze. *B*, direction of movement in land breeze.

*Made by dipping blotting-paper in a solution of potassium nitrate and drying it.

CHAPTER XLI

APPLICATIONS OF CONVECTION; RADIATION

262. Convection Currents in Cooking and Hot-water Supply. The distribution of heat for ordinary cooking operations, such as boiling, steaming, and oven-roasting and baking depends largely on convection currents.

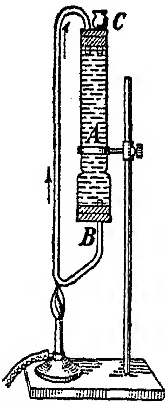


FIG. 275.—Illustration of the principle of heating water by convection currents.

When running water is available, kitchens are usually supplied with equipment for maintaining a supply of hot water for culinary purposes. The common method of heating the water by a coil in the fire-box of a stove or by a gas-heated coil is illustrated in the following experiment:

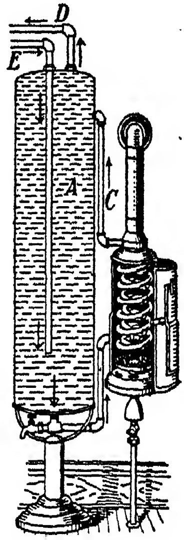


FIG. 276.—Connections in a water heater. The water tank A is connected with the copper coil in gas heater alongside. The arrows show the direction in which the water moves.

Experiment. Use a lamp chimney or a piece of tubing as a reservoir A and fit up the connecting tube as shown in Fig. 275. Drop a crystal or two of potassium permanganate to the bottom of the reservoir to show the direction of the water currents. Fill the reservoir and tube through the funnel C and heat the tube B with a lamp. A current will be observed to flow in the direction of the arrow. The hot water rises and enters at the top of the reservoir, and the cold water at the bottom moves forward to be heated.

Fig. 276 shows the actual connections in a kitchen outfit. The cold water supply-pipe E is connected with a tank in the attic or with the water-works service pipes. The hot water is drawn off through the pipe D.

QUESTION

In Fig. 276, why is the cold water supply pipe E continued to near the bottom of A? Trace the water flow from E through C to D.

263. Hot-water Heating. Hot-water systems of heating dwelling houses also depend on convection currents for the distribution of heat.

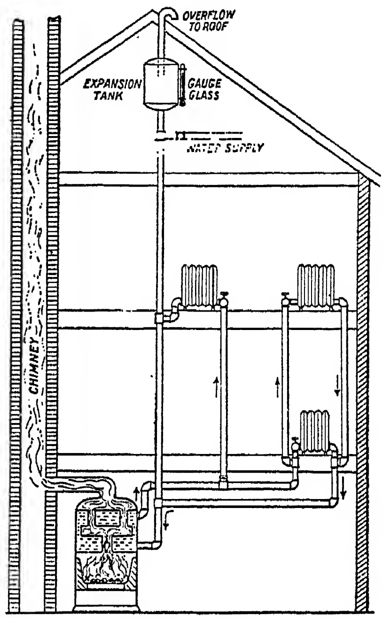


FIG. 278.—Hot-water heating system.

The principle may be illustrated by a modification of the last experiment. In the apparatus shown in Fig. 277 the lower end of the straight tube C is at the top of the flask A while the upper end is near the surface of the water in the open reservoir B. The bent tube D leaves B at the bottom and its lower end extends nearly to the bottom of A

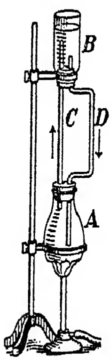


FIG. 277.—Illustration of the principle of heating buildings by hot water.

The system is filled with water, air-bubbles being carefully eliminated, and the water in B is coloured with potassium permanganate. When the flask A is heated the coloured water in B almost immediately begins to move downward through the tube D to the bottom of the flask, and the colourless water in C moves to the top of the reservoir.

In a hot-water heating system (Fig. 278) a boiler takes the place of the flask. The hot water passes through radiators in the various rooms of the house and then returns to the furnace. An expansion tank is also connected with

the system. Observe that, as in the flask, the hot water rises from the top of the heater and returns at the bottom.

264. Steam Heating. Steam also is employed for heating buildings. It is generated in a boiler and distributed by its own pressure through a system of pipes and radiators. As the steam condenses in the radiators it gives up its heat of vaporization (540 calories per gram). The water returns through the same pipes, or by separate return pipes as in the hot water system just described.

When the fire is checked the steam condenses in the radiators and the pressure inside falls below that of the atmosphere. Air now enters through a valve at the upper part of the radiator. When the steam rises again in the pipes it drives the air out through the valve. The steam itself does not escape because its heat, by expanding a rod, automatically closes the opening.

Some systems are not fitted with valves but at installation the air is driven out by steam and the radiator is sealed. When the radiator is cool a partial vacuum is created and the water under this reduced pressure boils at a lower temperature. The steam system does not give the same regularity of heat delivery as do the hot-water and hot-air systems.

265. Heating by Hot-air Furnaces. Hot-air systems of heating are in very common use. In most cases the circulation of air depends on convection currents. The development of such currents by hot-air furnaces depends on the principle that if a jacket is placed around a heated body and openings are made in it at the top and the bottom, a current of air will enter at the bottom and escape at a higher temperature at the top. For example, a lamp shade of the shape shown in Fig. 279 forms such a jacket about a hot lamp chimney. When the air around the lamp is charged with

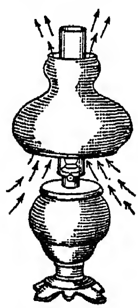


FIG. 279.—Air currents produced by placing a jacket around a heated body.

smoke, a current of air is seen to pass in at the base of the shade and out at the top.

A hot-air furnace consists of simply a stove with a galvanized-iron or brick jacket (*A*, Fig. 280) about it. Pipes connected with the top of the jacket convey the hot air to the rooms to be heated. The cold air is led into the base of the jacket by pipes connected with the outside air or with the floor of the room above.

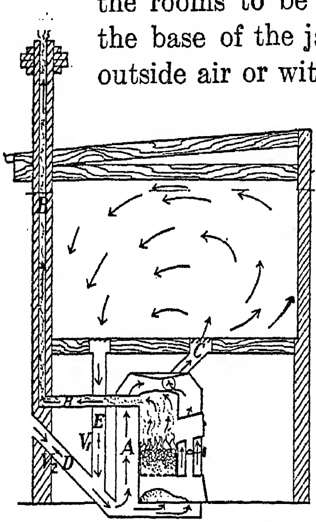


FIG. 280.—Hot-air heating and ventilating system. *A*, stove-jacket; *B*, smoke flue; *C*, warm-air pipe; *D*, cold-air pipe from outside; *E*, cold-air pipe from room; V_1, valve in pipe *E*; V_2, valve in pipe from outside. The air is thus kept in circulation.

266. Ventilation. Most of the methods adopted for securing a supply of fresh air for living rooms depend on the development of convection currents.

When a lighted candle is placed at the bottom of a wide-mouthed jar, fitted with two tubes, as shown in *B* (Fig. 281), it burns for a time but goes out as the air becomes deprived of oxygen and vitiated by the products of combustion. If one of the tubes is pushed to the bottom as in *A*, the candle will continue to burn brightly, because a continuous supply of fresh air comes in by one tube and the foul gas escapes by the other.

The experiment is typical of the means usually adopted to secure ventilation in dwelling houses. A current is made to flow between supply pipes and vents by heating the air at one or more points in its circuit.

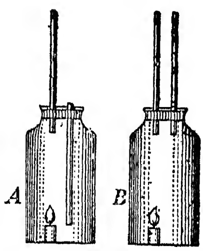


FIG. 281.—Illustration of principle of ventilation. The tubes should be at least ½ inch in diameter.

A warm-air furnace system of heating provides naturally for ventilation, if the

air to be warmed is drawn from the outside and, after being used, is allowed to escape. To support the circulation the vent flue is sometimes heated.

The supply pipes and vent flues are, as a rule, fitted with valves to control the air currents. When the inside supply pipe is closed and the others opened, a current of fresh air passes into and out of the house; when it is opened and the outside supply pipe and vent flue closed, the circulation is wholly within the house and the rooms are heated but not ventilated. Circulation is all-important.

With a hot-water or steam-heating plant ventilation must be effected indirectly. Sometimes a supply pipe is led in at the base of each radiator and fresh air drawn in by the upward current produced by the heated coils. More frequently coils are provided for warming the air before it enters the rooms. The coils are jacketed and the method for maintaining the current differs from the furnace system only in that the air is warmed by steam coils instead of by a stove. To secure a continuous circulation in large buildings under varying atmospheric conditions, the natural convection currents are often re-inforced and controlled by a power-driven fan placed in the circuit.

Much attention has been given in recent years to what is called air-conditioning, that is, to providing that the air in a given space—such as a living room, or lecture hall or a railway car—shall be pure and shall have the temperature and humidity most conducive to health. In order to do this there will be a heating plant for winter and a cooling plant for summer, as well as a means for evaporating water and driving the moisture-laden air where it is desired.

It will be interesting to calculate how much water will be required. Suppose we have a small living room of dimensions 13 x 20 x 9 ft. high. Its volume is 2340 cu. ft., which is 66 cu. m. Let the temperature be

68° F. or 20° C. From the table in § 245, 1 cu. m. of space at 20° C. if saturated will hold 17·2 gm. of water. If the R.H. is 50% it will hold 8·6 gm., and 66 cu. m. will hold 8·6 × 66 = 568 gm. of water which is 1 pint. Now if the air is changed once an hour (it should be oftener) then 24 pints or 3 gal. will be used up in 24 hours.

267. Convection in a Refrigerator. Convection currents in air may be utilized to keep an area cool as well as hot. This principle is applied in the ordinary household refrigerator (Fig. 282). Ice is placed in a chamber at the top, and provision is made for ventilation in such a manner that cool currents of air circulate over the perishable materials to be kept cool. The chamber is well insulated to prevent the entrance of heat from the outside.

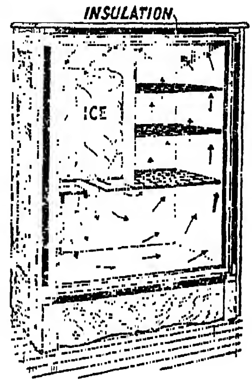


FIG. 282.—A household refrigerator with the front removed to show its construction.

QUESTIONS

1. Why is ice kept in the upper part of the refrigerator?

2. Why should hot water or steam radiators be installed near outside walls or windows on the cold side of a room?

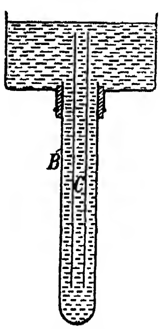


FIG. 283.

3. The apparatus shown in Fig. 283 is fitted up and filled with water until it rises a little above the end of the inner tube *C*. Describe the circulation in the water when a lamp flame is gently applied at the lower end of *B*. Fit up apparatus and try the experiment.

4. Is the draft through the fire of a furnace pushed through or drawn through? Explain.

5. Why is it difficult to make accurate measurements of the conduction of heat in liquids?

6. What transformations of energy take place in the process of keeping materials cold in a refrigerator?

7. Why is a hollow wall a better non-conductor of heat than a solid wall? What effect would filling the space with saw-dust or shavings have?

8. Why is it often difficult to heat rooms on the windward side of a house by using a hot-air furnace?

9. What provision is made in a hot-air furnace for humidifying the air? Why is such provision necessary?

10. Describe the heating and ventilating systems used in your school.

268. Transference of Heat by Radiation. Neither conduction nor convection will explain the transmission of heat across the ninety million miles of empty space between the earth and the sun. It is by **radiation** that the sun warms the earth. By getting in the shadow we shield ourselves from this direct effect; similarly the face may be protected from the heat of a fire by holding a book or paper between. **A hot body emits radiation in all directions and in straight lines; moreover, radiation can take place through a vacuum.** This is quite different from convection and conduction. Transmission by convection always takes place in one direction, namely, by upward currents; and conduction is not restricted to straight lines, for a bent wire conducts as well as a straight one.

269. Absorption and Radiation. When radiant energy falls upon a body, more or less of this energy is **absorbed,** and the temperature of the body rises. Some bodies have higher absorbing powers than others. Let us study this matter experimentally.

Experiment. Take two pieces of bright tin-plate about 4 inches square, and coat a face of one with lampblack. Then stand them parallel to each other and about 5 inches apart. They may conveniently be supported in saw-cuts in a board, and the blackened face should be turned towards the other plate. Attach with wax a bullet to the centre of the outer face of each plate. Now place midway between the plates a hot metal ball. Soon the bullet on the blackened plate will drop off while the other remains unaffected. If the blackened plate be touched with the finger, it will be found unpleasantly hot, while the other one will show a comparatively small rise in temperature.

We then conclude, **a black surface absorbs radiation well; a polished one absorbs it badly.** A polished surface reflects away the radiation which falls on it.

Next, let us compare the radiating powers of a black surface and a polished one.

Experiment. Use an apparatus like that illustrated in Fig. 284. It consists of two blackened bulbs connected by a tube in which is coloured water. Now place between the bulbs a well-polished vessel, one half of which is blackened, and fill it with hot water. On observing the change in the position of the coloured water it will be seen that the blackened surface is radiating much more heat than the polished half.

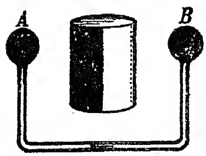


Fig. 284.—The blackened half of the vessel radiates more than the polished half.

We conclude that a **black surface radiates well; a polished one, badly.**

270. Radiometer. The Crookes radiometer (Fig. 285) exhibits the effect of absorption and radiation in an interesting manner. In its simplest form it consists of a bulb from which almost all of the air has been removed. Inside the bulb is a set of four thin aluminium vanes, blackened on one side and polished on the other. The vanes are carried on light aluminium spokes radiating from a central hub, which is pivoted on the point of a needle. When the radiometer is held in sunlight or close to any body emitting radiant energy, the black faces of the vanes absorb the radiation better than the bright faces. The air in contact with the blackened faces consequently becomes hotter than that in contact with the polished faces, and differences of pressure are set up which cause the vanes to revolve in such a way that a black face, when in sight of the source of the radiation, moves from the source.

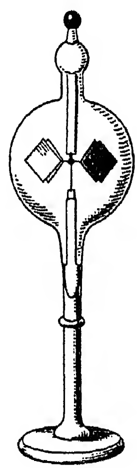


Fig. 285.—The Crookes Radiometer.

If a sheet of cardboard, or of any other substance which will not transmit radiant energy, is placed between the radiometer and the source the

vanes stop rotating, showing that radiation travels in straight lines.

QUESTIONS

1. Explain why a sheet of zinc protects woodwork from a stove better than a sheet of asbestos. Would bright tin-plate be better still?

2. A kettle to be heated by being hung before a fireplace should have one side blackened and the other polished. Why?

3. A sign consisted of gold-leaf letters on a board painted black. It was found, after a fire on the opposite side of the street, that the wood between the letters was charred while that under them was uninjured. Explain this phenomenon.

4. Why is a frost more likely with a clear sky than with a cloudy one?

5. Why is there a greater deposition of dew on grass than upon bare ground?

6. In the Sahara the cold at night and the heat by day are equally painful to bear. Explain why.

7. Covering a plant with paper often prevents it being frozen. Why?

8. How is (*a*) conduction, (*b*) convection, (*c*) radiation reduced to a minimum in the "thermos" bottle?

9. Describe the main differences between conduction, convection and radiation.

10. Why are the upper regions of the atmosphere very cold in spite of the fact that the radiant energy from the sun has to pass through these regions in order to reach the earth?

REFERENCES FOR FURTHER INFORMATION

G. D. Mallory, *Why You Should Insulate Your Home.*
The Insulation of Old and New Houses.
E. S. Martindale, *Humidity in House Heating.*

These three excellent pamphlets are published by the Dominion Fuel Board, Department of Mines and Resources, Ottawa.

CHAPTER XLII

HEAT AND MECHANICAL MOTION

271. Mechanical Energy and Heat Energy. Mechanical motion arrested by friction or percussion becomes transformed into heat energy. On the other hand, heat is one of our chief sources of mechanical motion. In fact, it is commonly said that modern industrial development had its beginning in the invention of the steam-engine. The development of the engine as a working machine is due to James Watt, a Scottish instrument-maker, who constructed the first engine in 1768. The *watt*, the unit of power defined in § 128, was named after him.

272. Mechanical Equivalent of Heat. We have referred (§ 180) to the fact that during the first half of the nineteenth century the kinetic theory of heat, advocated by Count Rumford and Sir Humphry Davy, gradually superseded the old materialistic conception. The establishment of the modern theory dates from about the middle of the century when Joule demonstrated that for every unit of mechanical energy which disappears in the transformation of mechanical motion into heat a definite and constant quantity of heat is developed.

The quantity of mechanical work which must be expended to produce one unit of heat is called its mechanical equivalent.

273. Determination of the Mechanical Equivalent of Heat. The essential features of Joule's apparatus for determining the mechanical equivalent of heat are illustrated in Fig. 286. A paddle-wheel was made to revolve in a vessel of water by a falling weight connected with it by pulleys and cords. Joule measured (1) the heat produced when the water was stirred up by the paddle, and (2) the corresponding amount of work

done by the descending weight. He calculated that one B.T.U. of heat was equivalent to 772 foot-pounds of mechanical energy. Later investigations by Rowland and others placed the relation at 778 foot-pounds for one B.T.U. of heat, which is equivalent to 4·187 joules (41,870,000 ergs), or 427 gram-metres of work for one calorie of heat.*

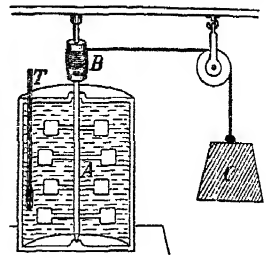


FIG. 286.—Principle o paratus for determining ical equivalent of heat.

274. Steam-engine. The essential working part of the ordinary type of steam-engine is a cylinder in which a piston is made to move backward and forward by the pressure of steam applied alternately to its two faces. To understand how this to-and-fro motion is kept up, study Figs. 287, 288. The steam from the boiler is conveyed by a pipe into the steam-chest. From the steam-chest the steam is admitted to the cylinder by openings called ports, *A* and *B*, at the ends of the cylinder. The exhaust steam escapes from the cylinder by the same ports. The admission of the steam to the cylinder, and its escape after it has performed its work, is controlled by the operation of a slide-valve. This valve is so adjusted that when the port *A* is connected with the steam-chest, *B* is connected with an exhaust pipe *P*, leading to the open air or to a condenser; and when *B* is connected with the steam-chest, *A* is connected with the exhaust pipe. Fig. 287 shows the steam entering at *A* and escaping at *B*. The piston, therefore, is being forced to the right. Meanwhile, the valve is being pushed in the opposite direction, and at the end of the stroke allows the steam to enter the cylinder at *B* and escape at *A* (Fig. 288). The piston is now being forced to the left. At the end of this stroke the steam again enters at *A* and escapes at *B* (Fig. 287). A

*For units of energy see § 128.

to-and-fro motion of the piston is thus kept up. This motion is transformed into a rotary motion in the shaft by a crank mechanism. Fig. 289 shows how this is effected in a very common type of engine.

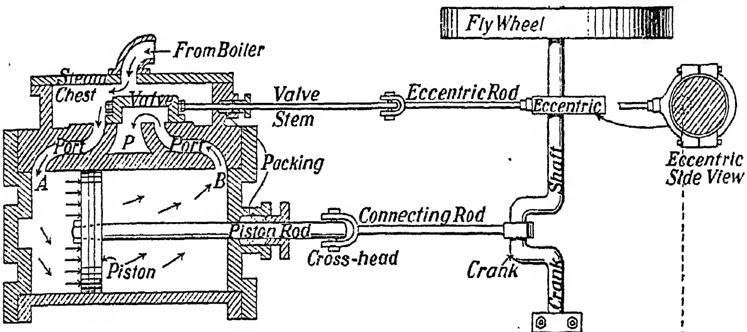


FIG. 287.—Showing the interior of the cylinder of a steam-engine. Steam entering port A, piston moving to the right.

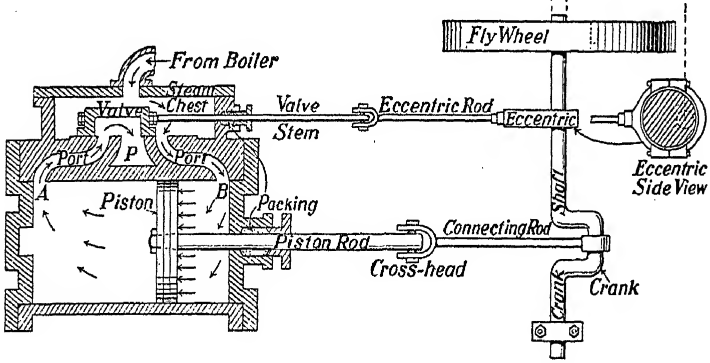


FIG. 288.—Steam entering at port B and piston moving to left.

The motion of the piston is transmitted through the piston-rod, the cross-head with its guides, and the connecting-rod to the crank, which is made to move in a circle about the centre of the shaft. The backward and forward motion of the piston is thus transformed by the connecting-rod into

a rotary motion in the shaft and the fly-wheel. The fly-wheel serves to give steadiness to the motion and to carry the engine over the "dead centres" at the ends of the strokes.

The valve is given its backward and forward motion by an eccentric keyed rigidly to the shaft of the engine (Fig. 289).

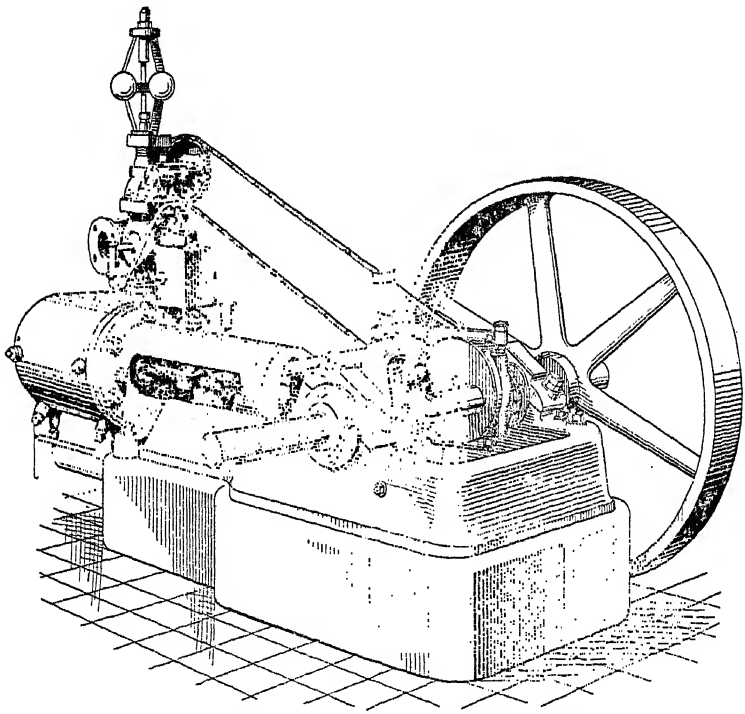
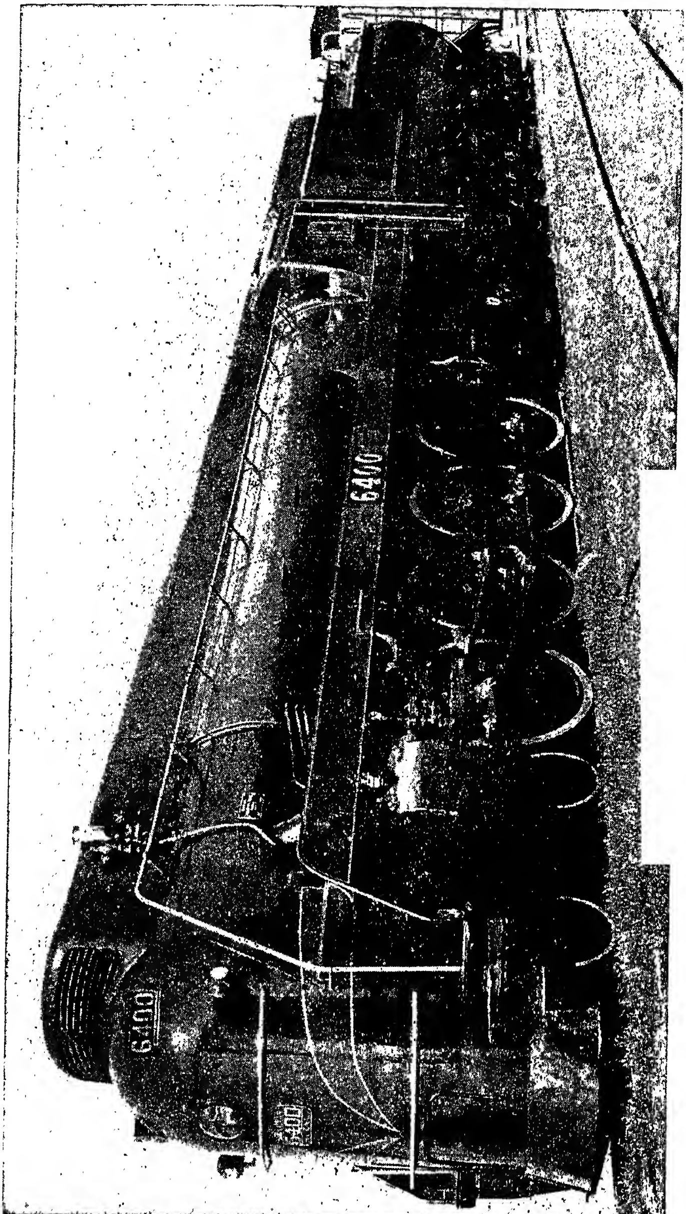


Fig. 289.—Showing the different parts of a steam-engine.

This eccentric consists of a circular metal disc having its centre at a distance from the centre of the shaft (Figs. 287, 288). When rotating, the centre of the eccentric will, accordingly, move in a circle about the centre of the shaft; consequently, the eccentric is made to do the duty of a crank. The motion of the eccentric is communicated to the valve-stem by the eccentric-rod (invisible in Fig. 289 as it is on the far side of the engine) and the collar, or strap,



PARTIALLY STREAM-LINED LOCOMOTIVE

● Plate 22

● **Plate 22**

The familiar smokestack, bell, cow-catcher and coupler are concealed by the streamlining which reduces the friction of the air when travelling at high speed.

The driving wheels are 77 in. in diameter and the overall length 94 ft. 8 in. Total weight of engine and tender in working order, 664,000 lbs.

(Photograph from Canadian National Railways)

within which it rotates. Compare the positions of the eccentric and the valves in Figs. 287 and 288.

Exercise. Obtain a working model of a steam-engine and note the relative positions of the piston, the connecting-rod, the crank, the eccentric, the eccentric-rod, and the valve as the fly-wheel is slowly rotated by hand.

275. High and Low Pressure Engines. In the common "high pressure" engine, the steam escapes from the cylinder directly into the air. In the low pressure, or condensing engine, the exhaust is led into a chamber (Fig. 290), where it is condensed by jets of cold water. The water is removed by an "air-pump."

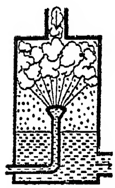


Fig. 290. — Condenser of "low pressure" steam-engine.

Since a more or less perfect vacuum is maintained in the condensing chamber of a low pressure engine, it will work under a given load at a lower steam pressure than the high pressure engine, because its piston does not encounter the opposing force of the atmospheric pressure.

276. The Compound Engine. When the pressure maintained in a boiler is high, the steam escapes from the cylinder of an engine with energy capable of further work. The purpose of the compound engine is to utilize this energy latent in exhaust steam. In this type, two, three or even four cylinders with pistons connected with a common shaft are so arranged that the steam which passes out of the first cylinder enters the next, which is of wider diameter, and so on, until it finally escapes into a condensing chamber connected with the last cylinder.

277. Turbine Engines. These are now being generally used in fast ocean-going steamships and many large steam power-plant installations. In this form of engine a drum attached to the main shaft is made to revolve by the impact of steam directed by nozzles against blades attached to its outer surfaces as shown in principle in Fig. 291. In actual construction there are numerous nozzles, moving blades and stationary blades, arranged with the utmost precision on the surface of the drum on the rotating shaft.

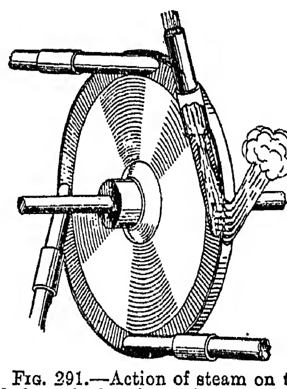


Fig. 291.—Action of steam on the blades of the drum in a turbine engine.

278. Gas-engines. The remarkable development of automobiles, tractors, and aeroplanes during the last quarter-century has been made possible by improvements in gas-engines. They are used for a multitude of purposes,—in launches and as auxiliary power in sailing craft; also for pumping water, generating current for electric light, and furnishing power for other purposes, more particularly on farms and in suburban districts where the other common sources of power are not available.

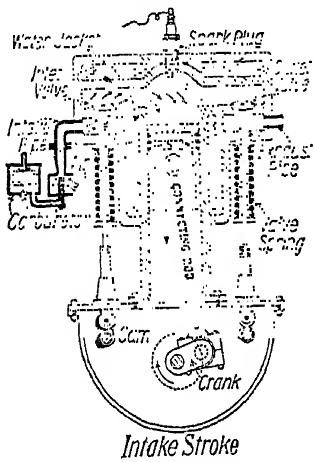


Fig. 292.—Intake Stroke.

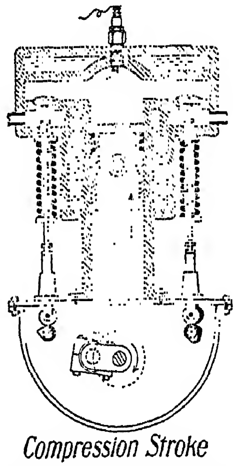


Fig. 293.—Compression Stroke.

The gas-engine is described as an "internal combustion" engine, because the fuel used is burned in the cylinder of the engine itself, and the piston is driven forward by the expansion of the heated gases produced in the combustion. The fuel most commonly used is an explosive mixture of gasoline vapour and air, but in the Diesel engine, which is used in submarines and in other vessels, heavier oils are utilized.

Gas-engines are of two types, the *four-stroke-cycle*, or simply *four-cycle*, engine and the *two-stroke-cycle*, or *two-cycle*, engine.

The four-cycle engine is the type most commonly used. In this form of engine, the piston receives an impulse at the

end of every fourth single stroke. To understand the action of the engine in each of the four strokes, consider Figs. 292-295. The shaft is turning clockwise, as shown by the arrows.

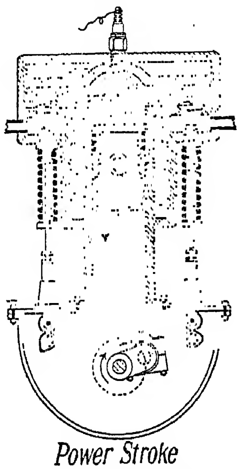


FIG. 294.—Power Stroke.

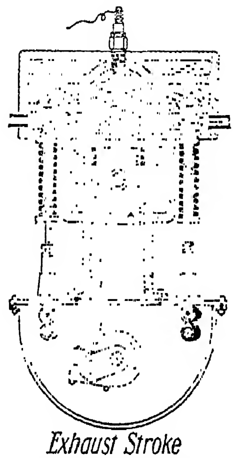


FIG. 295.—Exhaust Stroke.

In the intake stroke (Fig. 292), the piston is moving downward, and a charge of the combustible gas from the carburetor is drawn into the cylinder through the inlet valve, which has been raised for the purpose by the cam pushing up the rod which carries the valve. The inlet valve is closed by the valve-spring before the piston reaches the lowest point of its motion. As the piston moves upward in the next, or compression, stroke (Fig. 293), the charge, which was drawn into the cylinder during the intake stroke, is compressed into about one-fifth of its volume. At a properly timed instant the compressed charge is ignited by an electric spark at the point of the spark-plug, electrically connected with an induction coil and battery, and the piston is forced downward by the expansive force of the inclosed gases. This is the third, or power, stroke (Fig. 294). Before the piston begins its upward movement, the outlet valve is opened by the action of the cam, and as the piston is forced upward during

the last, or exhaust, stroke, the burnt gases escape from the cylinder (Fig. 295). Before the end of this stroke, the outlet valve is closed by the spring, and the engine is again on the point of taking in a new charge of fuel. In Fig. 296 is a simplified diagram showing the four .strokes of the cycle.

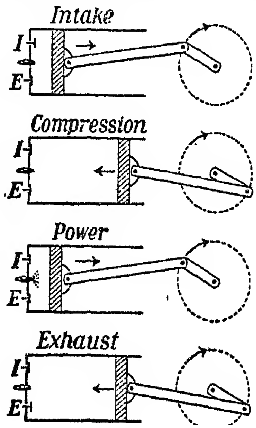


Fig. 296.—Diagram showing the four strokes.

The momentum given the balance wheel at each explosion serves to maintain the motion until the piston receives the next impulse. To cause the pressure to be more continuous in high-speed engines, from 2 to 16 cylinders have their pistons connected to a common shaft.

279. Two-cycle Engine. The two-cycle engine differs from the four-cycle, in that the piston receives an impulse at the end of every second single stroke. This is accomplished as follows: Consider Fig. 297. The piston has just descended and has finished the power stroke. As it nears the end of this stroke, the exhaust port *D* is uncovered to allow the products of combustion to escape and a very short time later the port *B* is uncovered and the new charge (previously compressed slightly in the crank-case) is admitted to the cylinder, where it is deflected upwards by a projection on the top of the piston and assists in

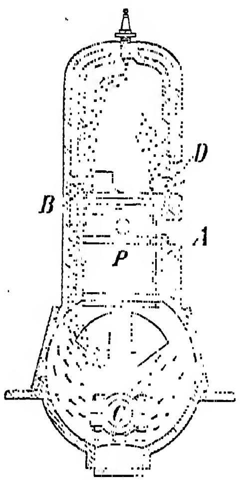


Fig. 297

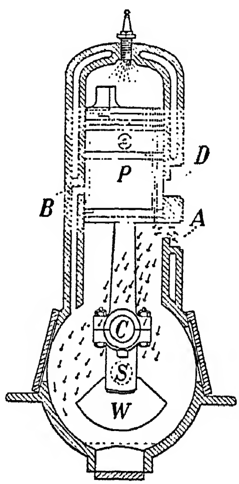
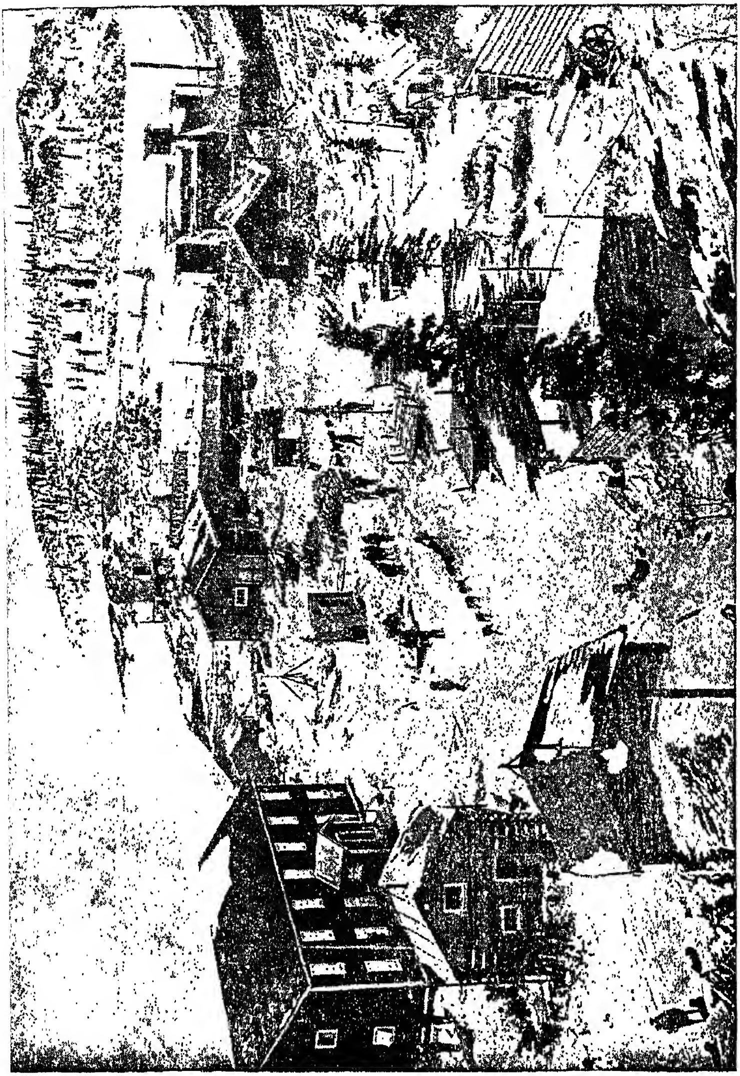


Fig. 298

Working parts of a two-stroke gas engine. *P*, piston; *S*, main shaft; *C*, crank pin; *A*, inlet port to crank chamber; *B*, inlet port to cylinder; *D*, exhaust port; *W*, counterpoise weight.



ELDORADO MINES, GREAT BEAR LAKE, N.W.T.

• **Plate 23**

The mines are on the east shore of the lake, 26 miles from the Arctic Circle. In 1930 Gilbert La Bine discovered the pitchblende veins which contain radium and uranium.

Note the mine buildings and the oil tanks at the rear, the bunkhouse middle left and the dog train in the centre.

(Photograph from Eldorado Mines)

sweeping out the burnt gases. In Fig. 298 the piston has reached the limit of the up stroke during which the ports B and D were closed and the new charge compressed above the piston, while another charge was admitted to the crank-case through the port A which was uncovered near the end of the stroke. The spark is just occurring to fire the mixture for the next power stroke.

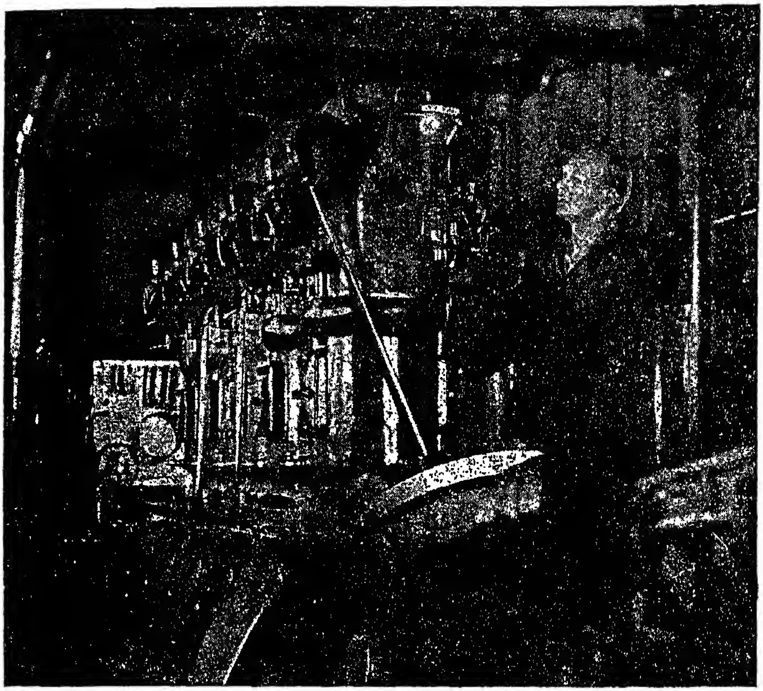


FIG. 299.—Diesel Engine

The above engine is at the Eldorado Gold Mines at the east end of Great Bear Lake, less than 30 miles from the Arctic Circle. It supplies electric power to mine and to mill radium, uranium, silver and copper. The engine was shipped by rail to Waterways, Alberta, and then transported by boat and portage over the 1500-mile Mackenzie system of rivers and lakes. It operates on fuel oil from the oil wells at Fort Norman, 250 miles to the west, on the Mackenzie River. The sinking of the first well there was completed in August 1920, and as the oil could not be marketed the well was capped, but the oil was available when needed. The mines were prospected in 1930 by Gilbert LaBine, and are the world's greatest source of radium. (See Plates, 23, 34, 35, facing pages 288 and 636.)

280. The Diesel Engine. In the internal-combustion engine, which we have just described, the explosive mixture must not be compressed too much lest it should be ignited by the heat produced by the compression. In the four-stroke cycle Diesel engine air alone enters during the intake stroke. This air is then compressed to about one-twelfth of its original volume and becomes very hot. The fuel oil,

which is similar to that used in oil furnaces, is injected into the cylinder at the beginning of the power stroke and ignites as soon as it meets the hot air, no spark being needed. In the exhaust stroke the products of combustion escape as in the ordinary gas engine.

Because of the high temperature at which this engine works it is able to burn low-grade oils which would not vaporize in the lower compression engine. This reduces the cost of operation. Diesel engines have replaced steam engines for many marine purposes and are also being used extensively on land (Fig. 299)

281. Efficiency of Heat Engines. All heat engines are wasteful of energy. The ordinary high-pressure steam-engine in everyday use utilizes not more than 5 per cent. of the energy latent in the fuel, while a very good type of triple-expansion marine engine will transform only about 17 per cent. of the heat of combustion into useful work. (In exceptional circumstances an efficiency of 22 per cent. has been reached.) The remainder of the heat energy is lost in the ash, in radiation from the boiler, pipes and engine, or is dissipated into the atmosphere by the smoke and exhaust steam. The best steam turbines are somewhat more efficient than the most economical forms of reciprocating engines.

The efficiency of the gas-engine is much higher than that of the steam-engine. Under best working conditions it will transform as high as 30 per cent. of heat energy into mechanical energy, while Diesel engines have attained an efficiency of 33 per cent.

QUESTIONS AND PROBLEMS

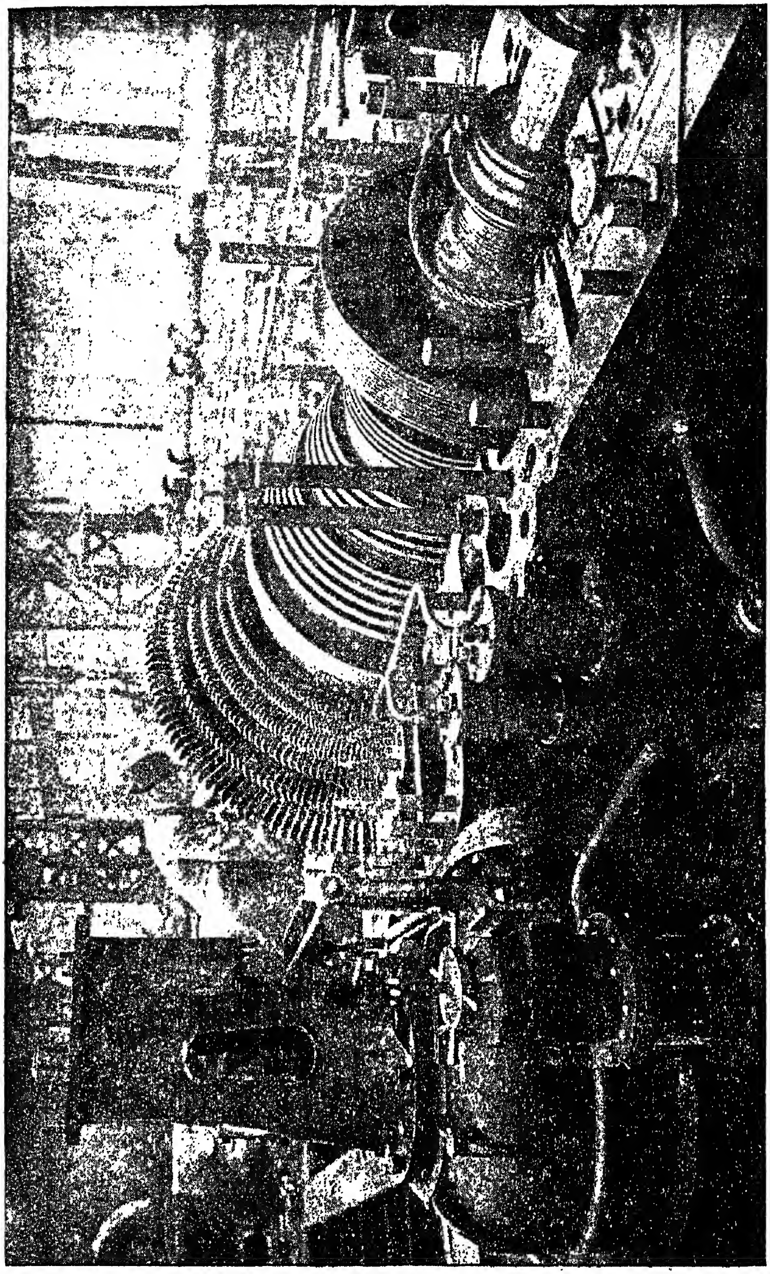
1. The water in the boiler of a steam-engine cannot be kept boiling at 100° C. Why?

2. How does the temperature of the gaseous products of combustion in the cylinder of a gas-engine at the moment of ignition compare with the temperature at the moment of exhaust? Explain.

3. Which is in the greater need of a heavy balance-wheel, (*a*) a one-cylinder four-cycle engine or a four-cylinder four-cycle engine? (*b*) a one-cylinder four-cycle engine or a one-cylinder two-cycle engine? Why?

4. The average pressure on the piston of a steam-engine is 60 pounds per sq. inch. If the area of the piston is 50 sq. in. and the length of the stroke 10 in., find (*a*) the work done in one stroke by the piston; (*b*) how much heat, measured by B.T.U., was lost by the steam in moving the piston.

5. The coal used in the furnace of a steam pumping-engine furnishes on an average 7000 calories of heat per gram. How many litres of water

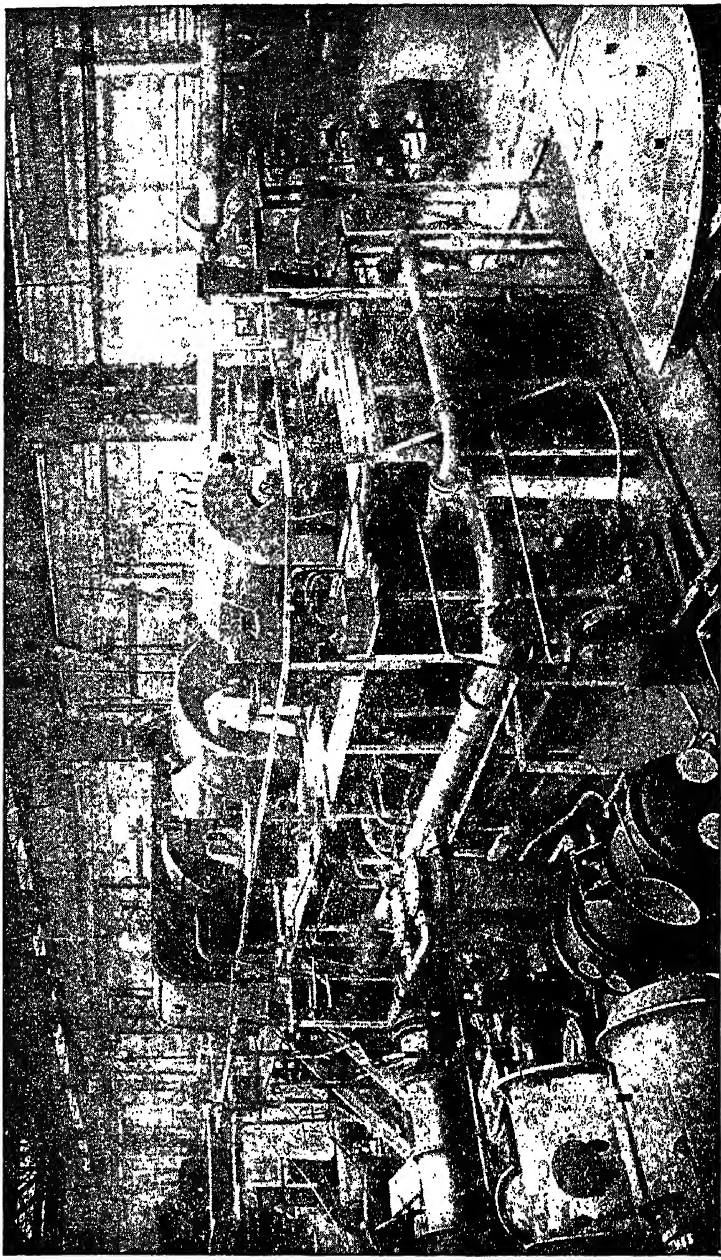


● Plate 24

Plate 24

This view shows the turbine shaft with its blading, the casing being removed. The steam enters the outer casing under a pressure of 800 pounds per square inch and a temperature of 800°F. and in passing between the blades produces a rapid rotation of the shaft. (See Plate 25).

(Photograph from C. A. Parsons & Co. of, Newcastle-on-Tyne, England)



STEAM TURBO-ALTERNATOR, COMPLETE

• Plate 25

This view was taken in the shops in England before shipment to Windsor, Ont., for the Ford Motor Company of Canada. It shows the piping below the floor as well as the machine above.

The shaft of this machine revolves 3,600 times per minute and generates alternating current at 13,800 volts. It develops 20,000 k.w. and is the largest of its kind in Canada.

(Photograph from C. A. Parsons & Co., of Newcastle-on-Tyne, England)

can be raised to a height of 20 metres by the consumption of 500 kg. of coal, if the efficiency of the engine is 5 per cent.?

6. Supposing that all the energy of onward motion possessed by a bullet, whose mass is 20 gm. and velocity 1000 m. per sec., is transformed into heat when it strikes the target, find in calories the amount of heat developed.

7. A train whose mass is 1000 tons is stopped by the friction of brakes. If the train was moving at a rate of 30 mi. per hr. when the brakes were applied, how much heat was developed?

8. How much coal per hr. is used in the furnaces of a steamer when the screw exerts a pushing force of 1000 kg. and drives the vessel at a rate of 20 km. per hr., if the efficiency of the engine is 10 per cent. and the coal used gives on the average 6000 calories of heat per gm.?

9. A locomotive whose efficiency is 7 per cent. is developing on the average 400 h.p. Find its fuel consumption per hr. if the coal furnishes 14,000 B.T.U.'s of heat per lb.

10. A modern steam turbine is able to deliver 1 h.p. for an hour on the consumption of 0·7 lb. of coal. If the coal furnishes 14,000 B.T.U. per lb., what percentage of the heat in the coal is used in producing mechanical power?

11. The following table gives a summary of the distribution of the heat from each pound of coal used in a condensing steam-engine plant:—

Lost in ash	100 B.T.U.
Lost in radiation from boiler	200
Carried off in smoke	2000
Lost in transmission	80
Lost in auxiliaries (feed-pump, etc.)	220
Lost in leakage and radiation from engine	200
Converted to work	2300
Rejected to condenser	8500
Total	13,600

Calculate the efficiency of the plant.

CHAPTER XLIII

PRODUCTION, PROPAGATION, VELOCITY OF SOUND

282. Sound arises from a Body in Motion. The sensation of sound arises from various kinds of sources, but if we take the trouble to trace the sound to its origin, we always find that it comes from a material body in motion. There are numerous ways to demonstrate this fact.

Pluck a violin or a guitar string and watch it closely. It has a hazy outline which becomes perfectly definite when the sound dies away. Double a bit of paper and hang it on the string and then vibrate it. The paper rider is at once thrown off. Place a finger on a sounding bell. You feel the movement, and when the sound ceases the movement does also. Next, touch the surface of water with the prong of a sounding tuning-fork. The water is formed into ripples or splashes up in spray. Or hang by a fine thread a light ball or a hollow bead against the sounding bell or tuning-fork. It will be thrown off vigorously.

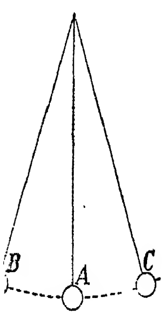


Fig. 300.—A simple pendulum.

All our experience leads us to conclude that in every case

ration.

283. Transverse Vibrations. Let us experiment with a simple pendulum such as that in Fig. 300.

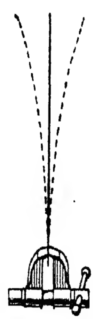


Fig. 301.—Transverse vibrations of a rod.

Pull the bob aside to B and let it go. It will swing backward and forward through A, its position when at rest. The motion from B to C and back again to B is a **complete vibration** or **cycle**; and the distance AB or AC is the **amplitude** of the vibration. The length of time it takes the bob to make a complete vibration is its **period**, and the number of complete vibrations or cycles made per second is its **frequency** or vibration number.

Next, clamp a thin metal strip at one end in a vice (Fig. 301), pull the free end aside and let it go. If the metal strip projects several inches from the vice we see it vibrate back and forth like a pendulum but do not hear any sound. However, if the projecting part is shortened successively to six, five, four . . . inches, the frequency increases and we are conscious of a humming note. The motion of the strip is communicated in some way to our ears and we receive a sensation of sound.

A violin string plucked at the centre vibrates in a similar manner.

Vibrations such as these, in which the motion is across the length of the vibrating body are called transverse vibrations.

284. Longitudinal Vibrations. The apparatus shown in Fig. 302 can be used to demonstrate the existence of a different kind of vibration.

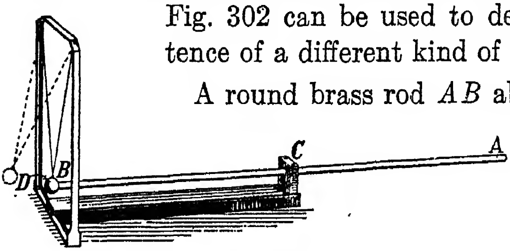


Fig. 302.—Illustrating longitudinal vibrations.

A round brass rod AB about 1 cm. in diameter and 100 cm. long is clamped at its middle point C, and an ivory ball D just touches the end B. Let us stroke the portion AC of the rod with a cloth on which is a little powdered rosin. A high musical note is produced, and at the same time the ball rebounds from the

end B vigorously, showing that the rod is in vibration in the direction of its length. In this case the ends A and B vibrate outwards from C and then back simultaneously while the centre remains perfectly steady.

These vibrations, in which the to-and-fro motion is in the direction of the length of the body, are said to be longitudinal vibrations.

285. Torsional Vibrations. By means of the apparatus shown in Fig. 303 a third kind of vibration can be illustrated.

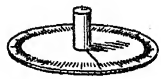


FIG. 303.— Illustrating torsional vibrations.

A metal cylinder with a pointer attached to it, is suspended by a wire over a graduated circle. Let us twist the cylinder about its axis and let it go. The wire untwists and twists and the pointer moves back and forth around the disc performing regular vibrations.

Next, grasp a piece of glass tubing about 2 cm. in diameter and 100 cm. long, at its middle with the left hand, and with a wet cloth in the right hand impart a twisting motion to the rod near the middle. The rod will twist and untwist like the wire in Fig. 303 and emit a high musical note.

Such vibrations are called **torsional vibrations.**

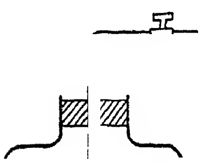


FIG. 304.—On exhausting the air from the bottle the sound of the bell becomes very faint.

286. Conveyance of Sound to the Ear. Most of the sounds which we hear travel from the vibrating body to our ears through air, but other substances can convey the sound as well.

By holding the ear against one end of a wooden rod, even a light scratch with a pin at the far end will be heard distinctly. One can detect the rumbling of a distant railway train by laying the ear upon the steel rail. The Indians on the western plains could, by putting the ear to the

ground, detect the tramping of cavalry too far off to be seen. If two stones be struck together under water, the sound perceived by an ear under water is louder than if the experiment had been performed in the air.

Thus we see that solids, liquids and gases all transmit sound. Further, we can demonstrate that some one of these is necessary.

In Fig. 304 is shown a bottle with a wide mouth fitted with a rubber stopper. Through the stopper passes a metal tube supplied with a stop-cock *A*. To the lower end of the metal tube is attached a piece of rubber tubing from which is suspended the small bell *B*. When the air inside is at ordinary pressure the sound of the bell is heard plainly on shaking the bottle, but if the air is drawn from the bottle by a good air-pump, the sound becomes feebler, continually becoming weaker as the exhaustion of the air proceeds.

If the air, or any other gas, or any vapour, is admitted to the bottle, the sound at once gets louder.

In performing this experiment it is likely that the sound will not entirely disappear, as there will always be some air in the bottle, and, in addition, a slight motion will be transmitted by the suspension; but we are justified in believing that a vibrating body in a perfect vacuum will not excite the sensation of sound.

In this respect sound differs from light and heat which come to us from the sun and the stars, passing freely through the perfect vacuum of space. **A material medium is needed for the transmission of sound.**

287. Velocity of Sound in Air. It is a common observation that sound requires an appreciable time to travel from one place to another. If we watch a carpenter working at a distance, we distinctly see his hammer fall before we hear the sound of the blow. Also, steam may be seen coming from the whistle of a locomotive or a steamboat several seconds

before the scund is heard, and we continue to hear the sound for the same length of time after the steam is shut off.

Some of the best experiments for determining the velocity of sound in air were made in 1822 by a commission appointed by the French Academy. The experiments were made between Montlhéry and Villejuif, two places a little south of Paris and 18·6 kilometers (or 11.6 miles) apart.

Each station was in charge of three eminent scientists and was provided with similar cannon and chronometers. It was found that the interval between the moment of seeing the flash and the arrival of the sound was, on the average, 54·6 seconds. This gives a velocity of 340·9 m. or 1118·4 ft. per second. Now the temperature was 15·9° C., and as the velocity increases about 60 cm., or 2 ft. per second for a rise of 1 Cent. deg., this velocity would be 331·4 m., or 1086·6 ft. per second at 0° C. Other experimenters have obtained slightly different results.

Velocity of Sound in Air

Temperature	Velocity, Per Second
0° C. = 32° F.	332 m. = 1089 ft.
15° C. = 59° F.	341 m. = 1119 ft.
20° C. = 68° F.	344 m. = 1129 ft.
− 45·6° C. = − 50° F.	305·6 m. = 1002 ft.

Experiments made to determine the velocity of the sound produced by the discharge of cannon have shown that the velocity at a distance of 100 ft. from a 10-inch gun is about 1240 ft. per sec., or 22 per cent. above normal; at 200 ft. from the gun the velocity is only about 5 per cent. above normal; and for all distances above 500 ft. from the gun the velocity of the explosive sound from even the largest sized gun is practically normal.

The velocity at − 50° F. was determined by Greely during his explorations in the Arctic regions, 1882-3.

QUESTIONS AND PROBLEMS

(Velocity of sound in air at 0°C. = 1089 ft. per sec.; velocity increases 2 ft. per sec. for each additional centigrade degree.)

1. Calculate the velocity of sound in air at 5°, 10°, 40° C.

2. An air-wave travelled about the earth (diameter 8000 mi.) in 36 hr. Find the velocity in ft. per sec.

3. A thunder-clap is heard 5 sec. after the lightning flash was seen. How far away was the electrical discharge? (Temperature, 15° C.)

4. The sound of a gun was heard 15 sec. after the flash was seen. If the temperature was 10° C., how far was the gun from the observer?

5. The velocity of a bullet is 2258 ft. per sec., and it is heard to strike the target 6 sec. after the shot was fired. Find the distance of the target. (Temperature, 20° C.)

6. In sound-ranging the explosion from an enemy gun is registered by a series of microphones arranged at intervals near the front-line trenches. If the sound-wave reaches three microphones *A*, *B* and *C*, so that *B* registers 1·5 sec. after *A* and *C* 2 sec. after *A*, how much farther is the gun from *B* and *C* than it is from *A*, the velocity of sound being 1120 ft. per sec.? (To find the position of the gun draw circles with these distances as radii, about *B* and *C*, and draw a third circle to pass through *A* and touch the circles. The gun is at the centre of this circle (Fig. 305).

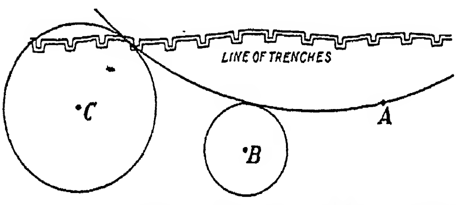


Fig. 305.—Locating an enemy gun by sound-ringing.

7. In 1826 two boats were moored on Lake Geneva, Switzerland, one on each side of the lake, 44,250 ft. apart. One was supplied with a bell *B* (Fig. 306*a*), placed under water, so arranged that at the moment it was struck a torch *m* lighted some gunpowder in the pot *P*. The sound was heard at the other boat by an observer with a watch in his hand and his ear to an ear-trumpet, the bell of which was in the water. Fig. 306*b*. The sound was heard 9·4 sec. after the flash was seen. Calculate the velocity of sound in water.

Fig. 306*a*.—Apparatus for producing the sound, in Lake Geneva.

Fig. 306*b*.—Listening to the sound from the other side of the Lak

8. Distinguish between transverse and longitudinal vibrations. Give

CHAPTER XLIV

SOUND: ITS TRANSMISSION; THE NATURE OF WAVES

288. Sound a Wave Motion. We have seen that for the hearing of a sound two things are necessary:

(1) A vibrating body.

(2) A material medium extending from the vibrating body to the ear.

Just how is the disturbance which is produced by the vibrating body transmitted to the ear?

Let us consider an analogy. Suppose we were standing on the shore of a lake and noticed a board floating on the water a short distance away. We might make the board move (1) by throwing stones at it, or (2) by setting up a wave motion on the water, which would soon travel out to the board causing it to move.

Similarly in the case of sound, the vibrating body might (1) send out material particles which would travel to the ear to produce the sensation, or (2) produce a wave motion in the intervening medium which would affect the ear.

We have good reason to believe that nothing material travels from the vibrating body to the ear. If this were the case how could sound travel through solids and why should it not travel through a vacuum?

Close investigation has led to the belief that the motion set up in the surrounding medium by the vibrating body spreads out from it in the form of waves, which, when they fall upon the drum of the ear, set it in vibration. This vibration affects the auditory nerve and we hear the sound.

We shall now proceed to learn something about wave-motion.

289. Chief Characteristic of Wave Motion. It is very interesting to stand on the shore of a large body of water and watch the waves, raised by a stiff breeze, as they travel majestically along. Steadily they move onward, until at last, crested with foam, they roll in upon the beach, breaking at our feet. The great ridges of water appear to be moving bodily forward towards us, but a little observation and consideration will convince us that such is not the case.

By watching a log, a sea-fowl, or any other definite object floating on the surface, we observe that, as the waves pass along, the object simply moves up and down, not coming appreciably nearer to us.

We see, then, that the motion of the water is handed on but not the water itself. In the case of a flowing stream the water itself moves and, perhaps, turns our water-wheels. Equally certain it is, however, that waves transmit energy, that is, ability to do work. A small boat, though at the distance of several miles from the course of a great steamer, will, sometime after the latter has passed, experience a violent motion, produced by the "swells" of the large vessel. No portion of the water has moved from one to the other, but yet it is the medium by which considerable energy has been transmitted.

A peculiar characteristic of wave motion is that, while the particles of water, or other medium, never move far from their ordinary positions of equilibrium, yet energy is transmitted from one place to another by means of the motion. In water waves, the particles do not simply move up and down. In deep water they move in circles in vertical planes, but as the water becomes shallow these circles are flattened into ellipses with their long axes horizontal.

290. Definition of Wave-length. If a long narrow trough containing water is available we can easily study miniature water waves. When a paddle (such as the lid of a chalk-box) is placed in the water near the middle of the trough and moved a few inches along the trough, the water piles up in front forming a crest, while a hollow is produced on the other side. The crest and hollow (or trough) then start moving along the water and continue until they reach the ends of the trough, where they are reflected.

Next let us move the paddle regularly back and forth in the water. We now find a continuous series of waves consisting of alternate crests and hollows moving out from the paddle in both directions.

A complete wave consists of a crest and a hollow and the continuous series of waves is called a wave-train.

The number of waves in such a train is indefinite; there may be few or many.

If now we look along such a train, we can select portions of it which are in exactly the same stage of movement, that is, which are moving in the same way at the same time. The

FIG. 307.—The distance *AB* or *CD* is a wave-length.

distance between two successive similar points, such as *A* and *B* or *C* and *D* (Fig. 307), is called **a wave-length.** It is usual to measure from one crest to the next one, but any other similar points may be chosen.

Particles which are at the same stage of the movement at the same time are said to be **in the same phase**; and so we can define a wave-length as **the shortest distance between any two particles whose motions are in the same phase.**

291. Refraction of Water Waves. It has often been observed that, when waves approach a shallow beach, the crests are usually approximately parallel to the shore line. In Fig. 308, *A*, *B*, *C*, etc., represent the successive positions of a wave approaching the shore. The dotted lines indicate the depth of water. It is seen that the end of the wave nearest the shore reaches shallow water first, and at once travels more slowly. This continues until at last the wave is almost parallel to the shore line.

This changing of the direction of the motion of the waves through a change in their velocity is called **refraction.**

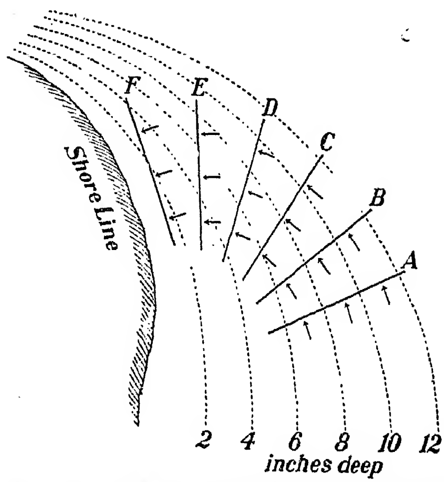


FIG. 308.—Diagram illustrating how a wave changes its direction of motion as it gets into shallower water, and is refracted.

292. Reflection of Waves. If, however, a train of water waves strike a precipitous shore or a long pier, they do not stop there, but start off again in a definite direction. This is illustrated in Fig. 309. The waves advance along *AB*, strike the pier and are reflected in the direction *BC*, the lines *AB*, *BC* making equal angles with *BD* the perpendicular to the pier. In sound and light we meet with many illustrations of reflection and refraction.

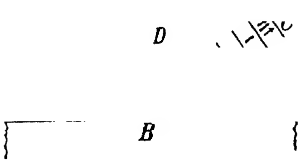


FIG. 309.—Water waves striking a long pier are reflected. (Looked at from above).

293. Transverse Waves in a Cord. Let one end of a light chain or rubber tube, 8 feet or more in length, be fastened to the ceiling or the wall of a room. Then, by shaking from side to side the free end, transverse waves will be formed and will pass freely along the tube. Here the hand is the vibrating body which sets up the wave motion in the tube.

We shall examine this motion more closely. Let us start with the tube straight as shown in (*a*), Fig. 310. The end *A* is quickly drawn aside through the space *AB*. The end particles drag the adjacent ones after them; these drag the next ones, and so on; and when the end ones have been pulled to *B*, the tube then has the form shown in (*b*).

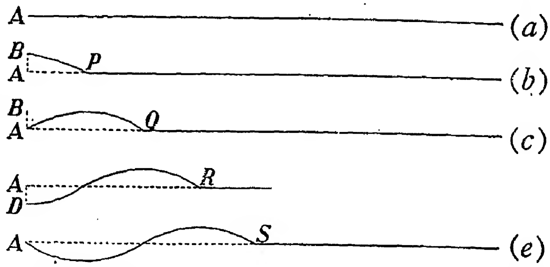


FIG. 310.—Diagram to show how a wave is formed and travels along a cord.

Instead of keeping the end at *B*, however, let it be quickly brought back to *A*, that is, the motion is from *A* to *B* and *B* to *A* without waiting at *B*. But the particles between *B* and *P* have been given an upward movement, and their inertia will carry them further, each pulling its next neighbour after it, until when the end is brought back to *A*, the tube will have the form *AQ*, shown in (*c*).

Suppose, next, that the hand does not stop at *A*, but that it continues on to *D*. On arriving there the tube will have the form (*d*). Immediately let the end be brought back to *A*, thus completing the 'round trip.' The tube will now have the form shown in (*e*).

Notice (1) that the hand has made a complete vibration or cycle, (2) that one wave has been formed, and (3) that the motion has travelled from A to S, which is a wave-length.

The **amplitude** of a vibration is the range on one side or the other of the middle point of the course. Thus *AB* or *AD* (Fig. 310) is the amplitude of the motion of the particle *A*.

294. Velocity, Frequency and Wave-length. In the preceding section we saw that while the body which started

the wave motion made one complete vibration or cycle, the wave motion travelled one wave-length.

Let the frequency or vibration number of the vibrating body be n cycles per second.

Then while the vibrating body makes n cycles the wave motion travels n wave-lengths.

Hence, the wave motion travels n wave-lengths in one second.

But the distance travelled in unit time (one second) is the velocity.

Therefore, if l = wave-length,

and v = velocity of transmission of the wave motion,

the wave motion travels nl in one second; or $v = nl$.

This is a very important relation; it holds for all kinds of wave motion, including sound, light, heat and radio waves.

295. Nodes and Loops. Next, let us keep the end of the rubber tube in continual vibration. A train of waves will steadily pass along the tube, and being reflected at the other end, a train will steadily return along it. These two trains will meet, each one moving as though it alone existed.

As the tube is under the action of the two sets of waves, the direct and reflected trains, it is easy to see that, while a direct wave may push downward any point on the tube a reflected one may lift it up, and the net result may be that the point will not move at all. The two waves in such a case are said to **interfere**.

That is just what does happen. By properly timing the vibrations of the end of the tube, the direct and reflected trains interfere, and certain points will be continually at rest.

(a)
(b)
(c)
(d)

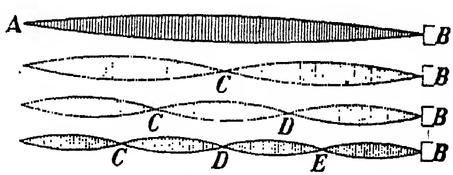


FIG. 311.—Standing waves in a cord. At A, C, D. E. B are *nodes;* midway between are *loops.*

If the end A (Fig. 311) is vibrated slowly, the tube will assume the form (a). On doubling the frequency, of vibration, it will take the form (b). By increasing the frequency other forms, such as shown in (c) and (d) may be obtained. In these cases the points A, B, C, D, E, are continually at rest and are called **nodes.** The portion between two nodes is called a **ventral segment,** and the middle point of it we shall call a **loop.** The distance between two successive nodes or loops is half a wave-length.

Such waves are called **stationary** or **standing** waves. As we have seen, they are caused by continual interference between the direct and the reflected waves.

296. Standing Waves. The most satisfactory method of producing the vibrations in a cord is to use a large tuning-fork, so arranged that the cord (which should be of silk, light and flexible) may be attached to one prong. In the absence of this the arrangement shown in Fig. 312

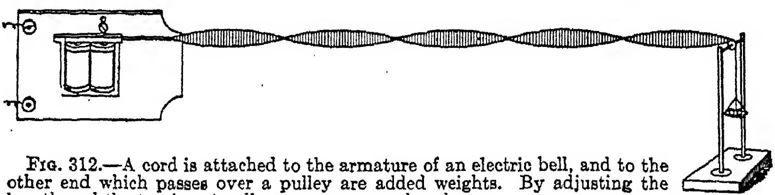


FIG. 312.—A cord is attached to the armature of an electric bell, and to the other end which passes over a pulley are added weights. By adjusting the length and the tension standing waves are produced.

may be used. The gong and the hammer of a large electric bell are removed. One end of the cord is attached to the armature, and the other passes over a pulley and has a pan to hold weights attached to it. In this way the length and the tension of the cord can be varied and the resulting standing waves studied.

QUESTIONS AND PROBLEMS

1. Outline two possible ways by which sound may be transmitted from a vibrating body to the ear.

2. What is a chief characteristic of wave-motion?

3. Define frequency and wave-length. When are two points said to be in the same phase?

4. Explain how water waves behave when they approach the shore, (a) if the water is shallow, (b) if it is deep.

5. Derive the formula connecting velocity, frequency and wave-length.

CHAPTER XLV

SOUND WAVES: THEIR NATURE AND THEIR VELOCITY IN SOLIDS AND GASES

297. Longitudinal Waves in a Spiral Spring. Let us consider a long spiral spring (Fig. 313). It should be 2 or 3 m.

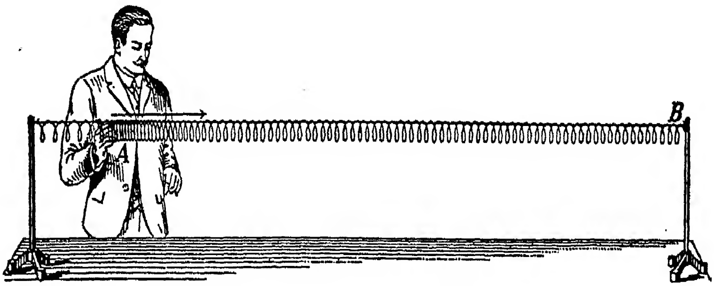


FIG. 313.—A convenient form of spiral spring.

long, and the diameter of the coils may be from 3 to 8 cm. To make such a spring one may take a hank of piano wire, slip it over a wire stretched between two supports and separate the coils, as shown in the figure.* Now insert the hand between two coils at A and by a quick push compress the coils together.

In this way the turns of wire in front of the hand are crowded together, and the turns behind, for about the same distance, are pulled wider apart. The compressed part of the spiral may be called a **condensation**, the stretched part a **rarefaction**.

Now watch closely and you will see the condensation, followed by the rarefaction, run with great speed along the spiral, and on reaching the end it will give a sharp thrust against the support B. Here it will be reflected and will

*Some makers of scientific instruments sell a much stiffer spring which works very well when lying on a long table stretched between two pegs.

return to the other end, from which it may be reflected and again return to B.

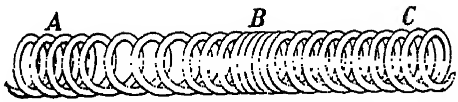


FIG. 314.—A wave consists of a condensation B, and a rarefaction A.

If a light object be tied to the wire at any place, it will be seen, as the wave passes, to receive a sharp jerking motion forward and backward in the direction of the length of the spiral.

On a closer examination we find that by applying force with the hand to the spiral we produce a crowding together of the turns of wire in the section B, (Fig. 314) and a separation at A. Instantly the elastic force of the wire causes B to expand, crowding together the turns of wire in front of it (in the section C), and thus causing the condensation to be transmitted forward. But the coils in B do not stop when they have recovered their original position. Like a pendulum they swing beyond the position of rest, thus producing a rarefaction at B where immediately before there was a condensation. Thus the pulse of condensation as it moves forward will be followed by one of rarefaction.

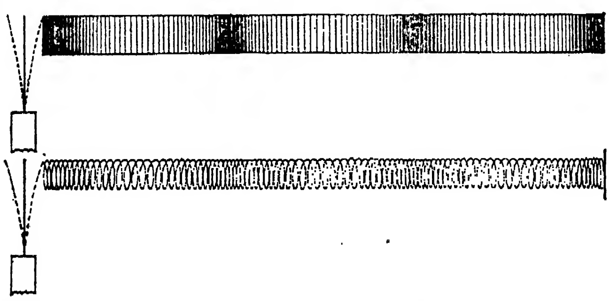


FIG. 315.—As the strip vibrates the air is alternately condensed and rarefied. A similar action takes place in the coil-spring.

298. Nature of a Sound-Wave. Air is similar to a spiral spring in that it may be compressed. Also, like a spring, it

will expand again when the pressure is released. Let a flat strip of metal be clamped in a vice or be otherwise held in a rigid support. Draw it aside, and let go. As it moves forward it compresses the air before it, and on its return the air on the same side is rarefied. With each complete vibration, or cycle, a complete wave, consisting of a pulse of condensation and a pulse of rarefaction, is produced.

After the strip has been vibrating for a short time the condition of the air on one side of the strip will be as shown in Fig. 315. We have a train of waves, each consisting of a condensation and a rarefaction. In the diagram the condensations are represented by lines crowded together.

A wave-length is the distance between successive condensations or rarefactions and it is evident that while the strip makes one complete vibration the sound travels one wave-length, l. If the strip vibrates n times, or performs n cycles, per second the sound will travel a distance nl in one second, or $v = nl$ where v is the velocity of sound.

The sound, however, does not go in just one direction as shown in Fig. 315, but it spreads out in all directions, as illustrated in Fig. 316, where spherical waves move out from the sounding bell as their centre.

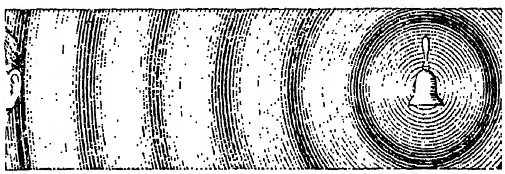


Fig. 316.- -Illustrating the transmission of sound in spherical waves.

It is evident that the vibrations of the particles of the medium in sound-waves are longitudinal.

299. An Air-Wave Encircling the Earth. A wonderful example of the spread of an air-wave occurred in 1883. Krakatoa is a small island between Java and Sumatra, in the East Indies, long known as the seat of an active volcano. Following a series of less violent explosions, a tremendous eruption occurred at 10 a.m. of August 27. The effects were stupendous. Great portions of the land, above the sea and beneath it, were displaced, thus causing an immense sea-wave which

destroyed 36,000 human lives, at the same time producing a great air-wave, which at once began to traverse the earth's atmosphere. It spread out circularly, gradually enlarging until it became a great circle to the earth, and then it contracted until it came together at the antipodes of Krakatoa, a point in the northern part of South America. It did not stop there, however, but, enlarging again, it retraced its course back to its source. Again it started out, went to the antipodes and returned. A third time this course was taken, and indeed it continued until the energy of the wave was spent.

The course taken by the wave was traced by means of self-registering barometers located at various observing stations throughout the world. As the wave passed over a station, there was a rise and then a fall in the barometer, and this was recorded by photographic means. In many places (Toronto included) there were four records of the wave as it moved from Krakatoa to the antipodes, and three of its return. In Fig. 317 is shown the rise in the barometer at Toronto caused by the second outward trip of the wave and the second return. The time required to go to the antipodes and return to Krakatoa was approximately 36 hours.

The sound of the explosion was actually heard, four hours after it happened, by human ears at Rodriguez, at a distance of over 2,900 miles

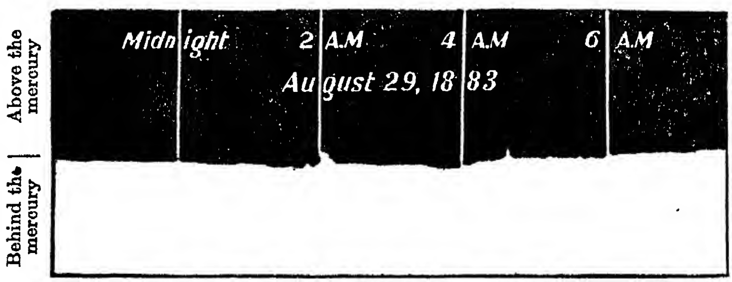


FIG. 317.—A portion of the photographic record of the height of the barometer at Toronto for August 29, 1883. To obtain the record, light is projected through the barometer tube above the mercury against sensitized paper which is on a drum behind the barometer. Every two hours the light is cut off and a white line is produced on the record. Shortly after 2 a.m., August 29, there was a rise, and at about 4.40 there was another. The former was due to the passage over Toronto of the wave on the second journey from Krakatoa to the antipodes; the latter was due to the second return from the antipodes to Toronto. (From the records of the Meteorological Service, Toronto.)

to the south-west. At the funeral of Queen Victoria, on February 1, 1901, the discharges of cannon were heard 140 miles away. In experiments performed during and after the world war explosions were heard 170 miles.

300. Velocity of Sound in Solids by Kundt's Tube. Having determined the velocity of sound in air, we can determine it in other gases and in solids by a method devised by Kundt in 1865.

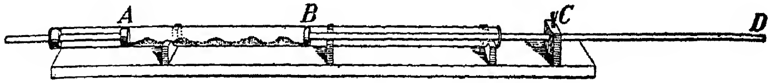


FIG. 318.—The little heaps of powder in the tube are produced by vibrations of the disc *B*.

BD (Fig. 318) is a brass rod about 80 or 100 cm. long and 8 or 10 mm. in diameter, securely clamped at the middle *C*. To the end *B* is attached a disc of cork or other light substance, which fits loosely into a glass tube about 30 or 35 mm. in diameter. *A* is a rod on the end of which is a disc, which slides snugly in the tube, thus allowing the distance between *A* and *B* to be varied. Dried precipitated silica, or simply powder made by filing a baked cork, is scattered along the lower side of the tube.

Now with a dry cloth or piece of chamois skin, on which is a little powdered rosin, stroke the outer half of the rod. With a little practice one can make the rod emit a high musical note. At the same time the powder in the tube is agitated, and by careful adjustment of *A*, the powder will at last gather into little heaps at regular intervals.

We must now carefully measure the length of the rod and also the distance between the heaps of powder, taking the average of several experiments.

By stroking the half *CD* of the rod we make it alternately lengthen and shorten, and the half *BC* elongates and shortens in precisely the same way. Thus the mid-point of the rod remains at rest, while all other portions of the rod vibrate longitudinally, the ends having the greatest amplitude.

It is evident that the middle of the rod is a node and the ends loops (§ 295), and hence if we had a very long rod and each part of it of length *BD* were vibrating in the same way, we should have standing waves in the brass rod, and *BD* would be one-half the wave-length.

Again, as the piston at *B* moves forward it compresses the air in front of it and as it retreats it rarefies the air. These air-waves travel along the tube and are reflected at *A* and return. The two sets of waves thus meet and interfere, producing stationary waves as explained in § 295 The powder gathers at the nodes, and hence the distance between the nodes is one-half the wave-length in air of the note emitted by the brass rod.

Example. In an experiment with a brass rod 5 ft. long the nodes were found to be $5\frac{3}{4}$ in. apart. The temperature of the room was 19° C. Find the frequency of the rod and the velocity of sound in brass.

Velocity of sound in air at 19° C. = 1127 ft. per sec.

Node to node in air = $5\frac{3}{4}$ in., and hence wave-length in air = $11\frac{1}{2}$ in.

Now $v = nl$, and substituting the values for v and l,

$1127 \times 12 = n \times 11\frac{1}{2}$, from which $n = 1176$ cycles per sec.

Also, loop to loop in brass = 5 ft. and wave-length in brass = 10 ft., and substituting in $v = nl$, we have $v = 1176 \times 10 = 11{,}760$ ft. per sec.

By using rods of different metals we can find the velocity in each of them.

301. Velocity in Different Gases.

The same apparatus can be used for different gases. To do so it is arranged as shown in Fig. 319.

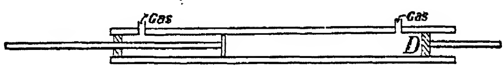


FIG. 319.—Kundt's method of finding the velocity of sound in different gases.

For this purpose a glass rod is preferable. It vibrates more easily by using a damp woollen cloth. It is waxed into the cork through which it passes. The piston D must be reasonably tight.

As before, measure the distance between adjacent heaps when the tube is filled with air. Let it be 5 in. Now fill it with carbon dioxide and let the distance be 4 in.

Then $v = nl$, and taking the velocity in air as 1120 ft. per sec.

$1120 \times 12 = n \times 10$, and $n = 1344$ vibrations per sec.

But the frequency $n = 1344$ is the same for each gas.

Hence for carbon dioxide $v = nl$ and $v \quad \frac{1344 \times 8}{12} = 896$ ft. per sec.

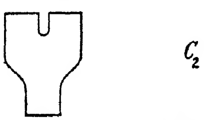


FIG. 320.— Koenig's fork, giving 65,586 cycles per sec. and his method of determining such large frequencies.

Koenig* used the dust tube (Fig. 320) for measuring high frequencies above the range of audibility. A small open tube containing some light fine powder was held with one end near the prong of a short stout tuning-fork which was struck by a mallet. The vibrations of the fork caused the powder to arrange itself in regular heaps from which the wave-length

*Karl Rudolph Koenig was born in Koenigsberg, Prussia, in 1832 and went to Paris in 1852 where he became famous as a maker of acoustical instruments, especially tuning-forks and wave-sirens. He died in 1901.

of the sound in air was measured and the frequency of vibration was then calculated as above. He actually measured frequencies up to 90,000 cycles, and constructed a fork giving 65,586 cycles per second.

VELOCITY OF SOUND IN SOLIDS, LIQUIDS AND GASES

Substance	Temperature	Velocity		Substance	Temperature	Velocity	
		m. per sec.	ft. per sec.		°C	m. per sec.	ft. per sec.
Aluminium		5104	16740	Water.....	9	1435	4708
Brass......		3500	11480	Carbon dioxide..	0	261·6	858
Copper....	20	3560	11670	Illum. gas.	0	490·4	1609
Copper....	100	3290	10800	Oxygen....	0	317·2	1041
Iron.......	20	5130	16820	Hydrogen..	0	1269	4165
Maple.....		4110	13470				

QUESTIONS AND PROBLEMS

1. At a certain temperature the velocity of sound in air is 1120 ft. per sec. Find the wave-length of the sound sent out by a tuning-fork whose frequency is 500 cycles per second.

2. In a Kundt's tube experiment the heaps of powder were found to be 4 in. apart when the tube was filled with air at 20° C. Find the frequency of the rod which produced the waves.

3. If the rod in Question 2 was made of iron and was 5 ft. long, find the velocity of sound in iron.

4. In a Kundt's tube a brass rod is 1 m. long, and five of the intervals between the dust-heaps equal 49·5 cm. Find the velocity of sound in brass in metres per second. (Temperature, 20° C.)

5. When a Kundt's tube is filled with hydrogen, the dust-heaps are 3·8 times as far apart as with air. Find the velocity of sound in hydrogen in feet per second. (Temperature, 20° C.)

6. A glass tube, 80 cm. long, held at its centre and vibrated with a wet cloth gives out a note whose frequency is 2540. Calculate the velocity of sound in glass in metres per second.

REFERENCES FOR FURTHER INFORMATION

BRAGG, *The World of Sound*, Lectures 3, 6.
CATCHPOOL, *Sound*, Chaps. 3, 9.
POYNTING AND THOMSON, *Sound*, Chap. 2.

CHAPTER XLVI

INTENSITY, PITCH

302. Musical Sounds and Noises. The slam of a door, the fall of a hammer, the crack of a rifle, the rattling of a carriage over a rough pavement,—all such disconnected, disagreeable sounds we call noises; while a note, such as that yielded by a plucked guitar string or by a flute, we at once recognize as musical.

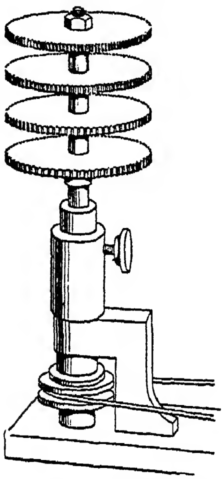


FIG. 321.—Toothed wheels on a rotating machine. On holding a card against the teeth a musical sound is heard.

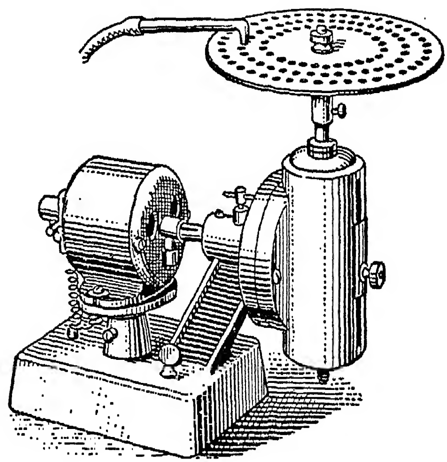


FIG. 322.—A disc siren. Air is blown through the holes in the rotating plate.

A musical note is a continuous, uniform and pleasing sound; while a noise is a shock, or an irregular succession of shocks, received by the ear.

Against the teeth on a rotating disc (Fig. 321) hold a card. When the speed is slow, we hear each separate tap as a noise, but as it is increased these taps at last blend into a clear musical note.

The same result, with a rather more pleasing effect is obtained by sending a current of air through holes regularly

spaced on a circle near the circumference of a rotating disc (Fig. 322). The little puffs through the holes blend into a pleasing note.

It is possible for a number of musical notes to be so jumbled together that the periodic nature is entirely lost, and then the result is a noise. If the holes in the disc (Fig. 322) are irregularly spaced we get a noise, not a musical note.

A musical tone is due to rapid regular vibration of a sounding body; a noise is due to irregular vibration.

303. Distinguishing Features of Sounds. Experience has taught us to recognize three features by which musical sounds can be distinguished from one another, namely,

(1) *Intensity or Loudness*, (2) *Pitch*, (3) *Quality*.

A violinist tunes a string on his instrument to a key on a piano. The notes are then of the same **pitch** no matter what the relative **intensities** may be; but they differ in an essential something called **quality**, which enables a person, even in the dark, to recognize that the one note comes from a violin and the other from a piano.

Quality will be considered more fully at a later stage.

304. Intensity of Sound. The intensity of sound depends on three things:

(1) *The energy of the vibrating body.* The amount of energy radiated per second is proportional to the square of the amplitude of the vibrating body. When we wish a tuning-fork or a stretched string to give a loud sound we bow it strongly so that it will have a large amplitude of vibration.

(2) *The density of the medium in which it is produced.* It is found that workmen in a tunnel in which the air is under pressure, though conversing naturally, appear to one another to speak in unusually loud tones, while balloonists and mountain climbers have difficulty in making themselves

heard when at great heights. The denser the medium, the louder is the sound.

(3) *The distance of the ear from the sounding body.* Suppose the sound to be radiating from O (Fig. 323) as centre, and let it travel a distance OA in one second. The energy will be distributed amongst the air particles on the sphere whose centre is O and radius OA.

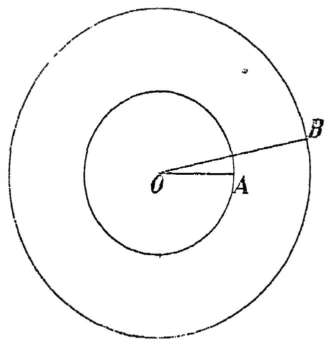


FIG. 323.—Diagram to show that the intensity of sound diminishes with the distance from the source.

In two seconds it will reach a distance OB, which is twice OA, and the energy which was on the smaller sphere will now be spread over the surface of the larger one. But this surface is *four* times that of the smaller, since the surface of a sphere is proportional to the square of its radius. Hence the intensity at B can be only one-fourth that at A, and we have the law that the intensity of a sound varies inversely as the square of the distance from the source.

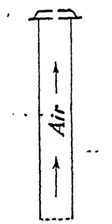
305. Transmission by Tubes. If, however, the sound is confined to a tube, especially a straight and smooth one, it may be transmitted great distances with little loss in intensity. Being prevented from expanding, the loss of the energy of the sound-waves is caused chiefly by friction of the air against the sides of the tube. If two rooms in a house are joined by a tube, words spoken in a low tone at one end will be heard at the other.

306. Reflection of Sound: Echoes. Every one has heard an echo. A sharp sound made before a large isolated building or a steep cliff, at a distance of 56 feet or more, is returned as an echo. The sound-waves strike the flat surface and are reflected back to the ear. If the distance is less than 56

feet the reflected sound arrives at the ear before the sensation produced by the original sound has disappeared and the ear is unable to distinguish the echo from the sound which produced it.

When there are several reflecting surfaces at different distances from the source of sound, a succession of echoes is heard. This phenomenon is often met with in mountainous regions.

In Europe there are many places celebrated for the number and beauty of their echoes. An echo in Woodstock Park (Oxfordshire, England) repeats 17 syllables by day and 20 by night. Tyndall says: "The sound of the Alpine horn, echoed from the rocks of the Wetterhorn or the Jungfrau [in Switzerland] is in the first instance heard roughly. But by successive reflections the notes are rendered more soft and flute-like, the gradual diminution of intensity giving the impression that the source of sound is retreating farther and farther into the solitude of ice and snow."



324.— n of a ll.

307. Laws of Reflection of Sound. The laws of reflection of sound are the same as those for light with which we are more familiar and which are explained fully in Chapter LVI. Experiments on the reflection of sound are not so easy to make as those on the reflection light. Best results are obtained with very short waves, that is, with sounds of very high pitch. These are conveniently produced by a bird call, which consists of two discs of thin metal very close together and mounted on the end of a brass tube (Fig. 324). There is a fine hole through the two discs and when a current of air is blown through the holes very rapid vibrations are sent out. In some bird calls the frequency is so high that the note is inaudible to the human ear. How then may they be detected?

FIG. 325.—Sensitive flame, (a) steady, (b) flaring

This is done by means of a sensitive flame. Gas from the mains or from a bag under pressure is passed through a small glass tube drawn out to a narrow opening. If the pressure is too great, the flame flares with a roaring sound (*b*, Fig. 325). If now the pressure is adjusted so that the flame is just on the point of flaring, as in *a*, any very high note, such as that from a bird call, a hiss or from shaking a bunch of keys will cause the flame to flare as in *b*.

The experiment on reflection is illustrated in Fig. 326. *A* and *B* are pieces of small stove-pipes or water-pipes placed at an angle of about 120°. When the flat reflector is set at the proper angle, as in the figure, pressing the bulb of the bird call will make the flame "duck down" and flare. Shaking a bunch of keys acts equally well.

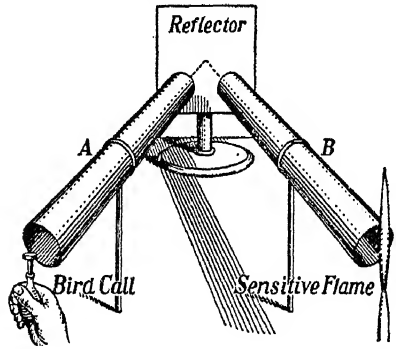


FIG. 326.—Demonstrating reflection of sound.

Hang a watch at the focus of a large concave mirror (Fig. 327). The sound waves strike the mirror, are reflected and then brought to a focus again by a second mirror. At this focus hold a funnel from which a rubber tube leads to the ear. The sound may be heard even though the mirrors are some yards apart.

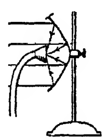


FIG. 327.—A watch is held in the focus of one concave reflector, and the ticking is heard at the focus of the other. (The foci can be located by means of rays of light.)

The experiment is more striking if for the watch a bird call is used and for the funnel a sensitive flame.

308. Other Examples of Reflection. The Mormon Tabernacle at Salt Lake City, Utah, is an immense auditorium, elliptic in shape,

250 feet long, 150 feet wide and 80 feet high, with seating accommodation for 8000 people. A pin dropped on a wooden railing near one end, or a whisper there is heard 200 feet away at the other end with remarkable distinctness.

The "whispering gallery" at St. Paul's Cathedral, London, is another notable example of reflection. A slight whisper uttered close to the wall on one side of the gallery is distinctly audible to an ear near the wall on the other side, a distance of 108 feet in a direct line or 160 feet round the semicircle. The sound "creeps" round by continuous reflections from the wall without ever getting far from it*. There is a whispering gallery at the Capitol in Washington.

When one speaks into a megaphone the sound is reflected by its walls and is confined largely to a definite direction. The energy is not dissipated by wide scattering. On the other hand, the telephone transmitter gathers the sound of the voice and directs it to the diaphragm of the microphone.

The bare walls of a hall are good reflectors of sound, though usually the dimensions are not great enough to give a distinct echo; but the numerous reflected sound-waves produce a *reverberation*, which appears to make the words of the speaker run into each other, and thus prevents them being distinctly heard. By means of cushions, carpets and curtains, which absorb the sound which falls upon them instead of reflecting it, this reverberation can be largely overcome. The presence of an audience has the same effect. Hence, a speaker is heard much better in a well-filled auditorium than in an empty one. An acoustical plaster, seven times as absorptive of sound as ordinary plaster, as well as other materials have been devised in order to reduce the reverberation.

309. Submarine Bell. A valuable application of the fact that water is a good conductor of sound is made in a method for warning ships from dangerous places. Light-houses and fog-horns have long been used, but the condition of the atmosphere often renders these of no avail. Submarine signals, however, can be depended upon in all kinds of weather.

The submarine bell, which sends out the signals (Fig. 328), is hung from a tripod resting at the bottom of the water or is suspended from a lightship or a buoy. The striking mechanism is actuated by compressed air or electricity supplied from the shore or the lightship.

The receiving apparatus is carried by the ship. Two iron tanks are located in the bow of the vessel, one on each side (Fig. 329). These tanks are filled with salt water, and the ship's outer skin forms one side of the tank. Suspended in each tank are two microphones (§ 586,)

*See Bragg, *The World of Sound*, p. 8.

which are connected to two telephone receivers up in the pilot-house. The officer on placing these to his ears can hear sounds from a bell even when more than 15 miles away; and by listening alternately to the sounds from the two tanks he can accurately locate the direction of the bell from him. Signal stations operating submarine bells are to be found on the shores of various countries, several being located in the lower St. Lawrence and about the maritime provinces of Canada.

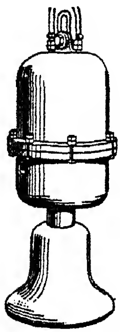


Fig. 328.—Submarine bell, worked by compressed air supplied from the shore. The mechanism for moving the hammer of the bell is contained in the upper chamber.

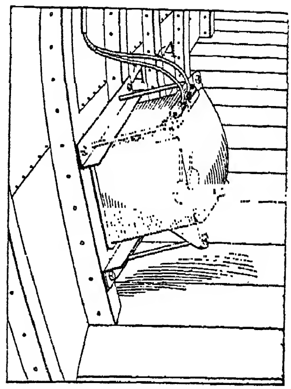


Fig. 329.—The sound from the bell is received by two tanks placed in the forepeak of the ship, one on each side. The tank is filled with salt water, and the ship's outer skin forms one of its sides. In the water are two microphones, which are connected by wires A, A to two telephone receivers up in the pilot-house.

310. Sounding the Ocean by Sound-waves.

Recently an efficient method of determining the depth of the ocean by means of sound-waves has been devised, the operation being very similar to that just described. The sound-producer, and also the sound-receivers, are carried on the ship. A sound is produced, and the exact instant when it starts out is observed. It travels to the floor of the ocean, is reflected there and returns, and

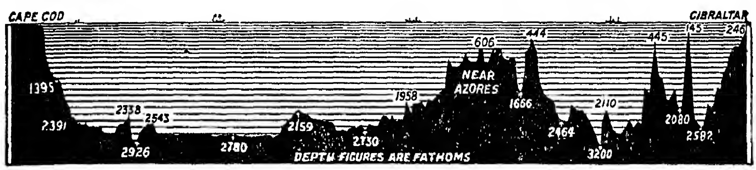


Fig. 330.—Contour of ocean floor between Cape Cod and Gibraltar.

the precise instant when it gets back is also observed. In the interval between these two instants the sound has travelled twice the depth of the ocean, and, knowing the velocity in sea-water, the depth can be calculated. In Fig. 330 is shown the contour of the ocean floor as determined by a U.S. Navy ship on a trip from Cape Cod to Gibraltar, the passage being made at 17 miles per hour.

During the World War, 1914-1918, vibrations of a very high frequency were used in an effort to detect the presence of submarines. A small

quartz crystal was forced to vibrate under water by means of an oscillating electrical potential-difference applied to opposite faces. The very short waves (supersonics, above 40,000 per sec.) produced were transmitted through the water in a direction perpendicular to the face of the crystal. By directing the beam towards a ship or a rock or the sea bottom the outgoing waves were reflected, and on returning to the source were detected by a receiver. The harder the reflecting surface the more intense was the sound picked up by the receiver, and the observer was able to determine with considerable accuracy the nature of the reflecting surface. If an enemy submarine was located a suitable depth bomb was released.

QUESTIONS AND PROBLEMS

1. From what experience would you conclude that all sounds, no matter what the pitch may be, travel at the same rate?

2. Why does the presence of an audience improve the acoustic properties of a hall?

3. Explain the action of the ear-trumpet and the megaphone or speaking-trumpet.

4. At Carisbrook Castle, in the Isle of Wight, is a well 210 feet deep and 12 feet wide, the interior being lined with smooth masonry. A pin dropped into it can easily be heard to strike the water. Explain.

Find the interval between the moment of dropping the pin and that of hearing the sound. (Temperature, 15° C., $g = 32$.)

5. The captain of a ship can sometimes determine his distance from a shore by blowing a sharp blast on the whistle and counting the seconds until the echo is heard. Explain how the distance would be calculated.

6. The captain estimates the interval between blowing the whistle and hearing the echo is $2\frac{1}{4}$ sec. How far away is the shore. (Temperature 59° F.)

7. A man standing before a precipice shouts, and 3 sec. afterwards he hears the echo. How far away is the precipice? Temperature, 15° C.)

8. Assuming the velocity of sound in water to be 4708 ft. per sec., find the depth of the ocean at a point where a sound produced by a ship returns, after striking the ocean floor in 4·5 sec.

REFERENCES FOR FURTHER INFORMATION

Bragg, *The World of Sound,* Lectures 1, 3.
Tyndall, *Sound,* Chapter 6.
Watson, *Sound,* Chapter 21.
Chant and Burton, *A Text-Book of College Physics,* Chapter 50.

CHAPTER XLVII

FREQUENCY OF VIBRATION; MUSICAL SCALES

311. Determination of Pitch. The number of vibrations per second, or the frequency, corresponding to any given pitch may be determined by various devices. One is the toothed wheel shown in Fig. 321. Suppose we wish to find the frequency of a tuning-fork. The speed of rotation is increased until the pitch of the note given by the wheel is the same as that by the fork. Then the speed is kept constant for a certain time—say half a minute—and the number of turns of the crank in this time is counted and the rotations of the wheel per second deduced. Then on multiplying this number by the number of teeth on the wheel, we obtain the number of vibrations per second. The perforated disc may be used in the same way. Better results will be obtained with either wheel or disc if a motor-driven rotator and revolution-counter are used.

Example. A wheel with 64 teeth is found to give the same note as a tuning-fork when it makes 80 rotations in 20 seconds. Find the frequency of the fork.

The wheel makes $80 \div 20 = 4$ rotations per second.

Each rotation produces 64 vibrations.

Hence the frequency $= 4 \times 64 = 256$ v.p.s.

312. De la Tour's Siren. A more satisfactory instrument is that shown in Fig. 331 and known as a siren. It was invented by Cagniard de la Tour in 1819.

A perforated metal disc B rotates on a vertical axis, just above a cylindrical air-chamber C. The upper end of the chamber and also the disc are perforated at equal intervals along a circle which has as centre the axis of rotation. The upper and lower holes correspond in number, position and size, but they are drilled obliquely, those in the disc sloping

in a direction opposite to those in the end of the chamber. The tube *D* is connected with a bellows or other blower.

When the air is forced into the chamber and passes up through the holes, the disc is made to rotate by the air-current striking against the sides of the holes in the disc, and the more powerful the air-current the more rapid is the rotation.

Vibrations in the air are set up by the puffs of air escaping above the disc as the holes come opposite each other; and by controlling the air supply, we can cause the disc to rotate at any speed, and thus obtain a sound of any desired pitch.

Having obtained this sound, a mechanical counter, in the upper part of the instrument, is thrown in gear and keeping the speed constant for any time, this will record the number of rotations. The frequency is obtained at once by multiplying the number of rotations per second by the number of holes in the disc.

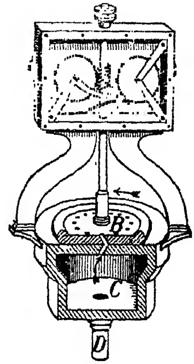


FIG. 331.—The siren. Air enters the chamber *C* by way of the pipe *D*, and on escaping causes the disc *B* to rotate.

A method depending on the principle of resonance is described in § 346.

313. Limits of Audibility of Sounds. Not all vibrations, even though perfectly periodic, can be recognized as sounds, the power of detecting these varying widely in different persons. For ordinary ears the lowest frequency which causes the sensation of a musical tone is about 27 per second, (the lowest note on the piano) the highest is about 16,000 per second, or two octaves above the highest note on the piano. The range of the human voice lies between 60 and 1300 vibrations per second, or more than 4½ octaves; a singer ordinarily has about two octaves.

314. Combinations of Musical Notes. A musical note is pleasing in itself, but certain combinations of notes are especially agreeable to the ear. These have been recognized amongst all nations from the earliest times, having been developed purely from the aesthetic or artistic side. The older musicians knew nothing about sound-waves and vibration numbers; they were guided by what gave them pleasure and appealed to their emotions.

But on measuring the frequencies of the notes of the pleasing combinations, we find that the ratios between them are peculiarly simple, and indeed that the more pleasing any combination is, the simpler are the ratios between the frequencies of the notes.

315. Musical Chords. Two or more notes sounded simultaneously constitute a **chord.** If the effect is agreeable it is called **concord**; if disagreeable, **discord.**

Let us take four tuning-forks mounted on resonance boxes and having frequencies of 256, 320, 384 and 512 vibrations per second. These give notes C, E, G and C' on the physicist's scale and it will be noted that these frequencies are proportional to the simple numbers 4, 5, 6 and 8. Let us try various combinations of these notes.

The most perfect chord is C, C', the ratio between the frequencies being $\frac{2}{1}$. The next is C, G, the ratio being $\frac{3}{2}$. Note that in these ratios we use only the small numbers 1, 2, 3.

When the notes C, E, G are sounded together, the effect is extremely pleasing. This combination is called a **major triad,** and when C' is added to it we get a **major tetrad.**

In a major triad the frequencies of the notes are in the ratios 4:5:6.

In a major tetrad the ratios are 4:5:6:8.

If the frequency of one note is twice that of another the latter is called the octave of the former. The ratio is 2:1.

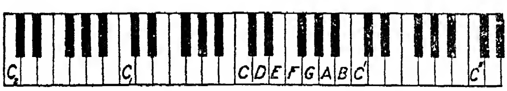


FIG. 332.—Central part of a piano key-board. The notes marked C_2, C_1, C, C' C'', go up by octaves.

316. The Octave. Pitch depends only on the number of vibrations per second; but as we compare notes of different pitch with one another—for instance the notes on a piano—

we are struck with the fact that when we have gone a certain distance upwards or downwards, the notes appear to repeat themselves. Of course the pitch is different, but there is a wonderful similarity between the notes.

On investigation a remarkable relation between the frequencies of the notes is revealed. As stated above, one note appears to be the repetition of another when their frequencies are as 1 to 2, and the second is the octave of the first.

Between the note and its octave custom has introduced six notes, the eight notes thus obtained being familiar to students of vocal music under the names

Doh, Ray, Me, Fah, Soh, Lah, Te, Doh'.

The notes are, however, more usually designated by letters; for example,

$$C, \quad D, \quad E, \quad F, \quad G, \quad A, \quad B, \quad C',$$

where the key-note is C. (Fig. 332).

As we pass from C to C' by these interpolated notes we do so by steps which are universally recognized as the most pleasing to the ear. This series of notes is called the **natural or major diatonic scale.**

317. Major Diatonic Scale. By actual experiment it has been found that, whatever the absolute pitch may be — whether high up in the treble, or low down in the bass— the ratios between the frequencies of the different notes are constant.

Suppose the note C has a frequency 256. The entire scale is as follows:

Names....	C	D	E	F	G	A	B	C'
Numbers..	256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512,
Ratios....	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2.

These ratios hold, whatever the absolute frequency may be. By international agreement the frequency of middle C of the piano is taken as 261, that of the A string of a violin

being 435 vibrations per second. The numbers for the scale are then,

261 293·6 326·2 348 391·5 435 489·4 522.

A close examination of the major scale shows that it is made up of repetitions of the major triad. Thus C, E, G; F, A, C' and

D E G B C' D'

G, B, D' are all major triads.

318. The Scale of Equal Temperament. In musical composition C is not always used as the first or key-note of the scale; any note may be chosen for that purpose. But with each new key-note several new notes must be introduced, and at last the total number of notes becomes so great that it would be impracticable to construct an instrument with fixed notes, such as the piano or the organ, to play in all the keys.

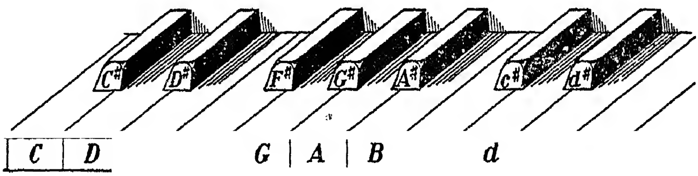


FIG. 333.—Showing the chromatic scale.

The difficulty is overcome by **tempering** the scale, that is, by slightly altering the intervals. In the **scale of equal temperament** the octave contains 13 notes represented by the eight white keys and the five black keys of the piano, and the ratios between the frequencies of adjacent notes are all equal. The 13 notes (the chromatic scale) are (Fig. 333):

C, $C\sharp$, D, $D\sharp$, E, F, $F\sharp$, G, $G\sharp$, A, $A\sharp$, B, c,

and the ratio between the frequencies of succeeding notes is 1·059 (or 1·06 approx.) which = $\sqrt[12]{}$

Taking the key-note to have a frequency of 256 the tempered scale is as follows, the true diatonic scale being added for comparison:

C	D	E	F	G	A	B	C'
256	287·3	322·5	341·7	383·6	430·5	483·2	512,
256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512.

If one starts with D as the key-note the scale is

$$D,\ E,\ F\sharp,\ G,\ A,\ B,\ c\sharp,\ d.$$

The tempered scale is not quite so pleasing as the true diatonic scale. An accomplished violinist may play the latter scale by properly placing his fingers. A choir of picked voices when singing unaccompanied uses the true intervals.

319. The Harmonic Scale. When a note is sounded on certain musical instruments, a practised ear can usually detect, in addition to the fundamental or principal tone, tones of other frequencies. These are much less intense than the principal tone. If the frequency of a tone is represented by 1, those tones with frequencies corresponding to 2, 3, 4, 5 . . . . are said to be harmonics of the tone 1, which is called their fundamental. The entire series is known as the **harmonic scale.**

In the piano these harmonics are prominent. In the tuning-fork, when properly vibrated, the harmonics almost instantly disappear, leaving a pure tone.

QUESTIONS AND PROBLEMS

1. Why does the sound of a circular saw fall in pitch as the saw goes farther into the wood?

2. A toothed wheel has 65 teeth and revolves 240 times per minute. Find the frequency of the note produced when a card is held against the teeth. Calculate also the wave-length of the sound, taking the velocity as 1120 ft. per second.

3. The counter of a siren (§ 312) registered 360 revolutions in 30 seconds. If the number of holes in the disc was 48, find the frequency of the note emitted by the instrument.

4. A wheel with 30 teeth is revolved so that when a card is held against the teeth a sound one octave above middle C, which has 261 vibrations

per second, is heard. How many revolutions per minute does the wheel make?

5. Four tuning-forks give the notes of a major chord. The lowest fork has a frequency of 512 vibrations per sec. Find the frequencies of the other forks.

6. The notes C, E, G and C' form a major chord. If G has a frequency of 384, find the frequencies of the other notes.

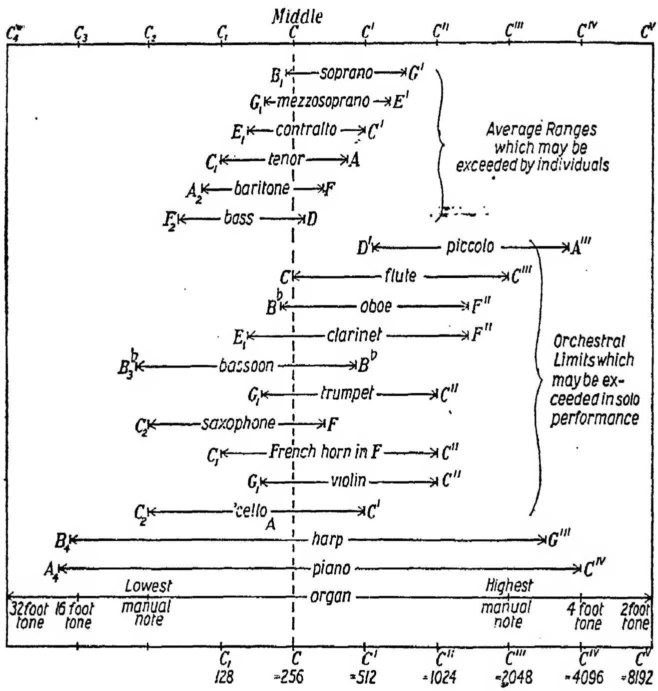
7. If the vibration number of C is 300, find those for F and A.

8. If the frequency of A were 452, what would be that of C?

9. Find the wave-length of D^{IV} (*i.e.*, four octaves above D) in air at 0° C., taking the frequency of C as 261.

10. Which note has 3 times the number of vibrations of C? Which has 5 times?

Chart showing the Ranges of Singers and of Musical Instruments



REFERENCES FOR FURTHER INFORMATION

BRAGG, *The World of Sound*, Lecture 2.
POYNTING AND THOMSON, *Sound*, Chap. 3.
CHANT AND BURTON, *A Text-Book of College Physics*, Chapter 49.

CHAPTER XLVIII

VIBRATIONS OF STRINGS

320. Frequency of a Vibrating String. Stringed instruments are widely used in music and consequently we should know something about the factors which determine the frequency of a vibrating string. If we examine a violin we find that it has four strings, each of which produces a different note as the violinist changes with his fingers the length in vibration. To tune any string to the proper frequency he alters **the tension** by turning a key to which the string is attached. The four strings differ in diameter and the *G* string is wrapped with copper wire to increase its average density. **The frequency of a vibrating string**

its length, tension, diameter and density.

321. The Sonometer. The vibrations of strings are best studied by means of the sonometer, a convenient form of which is shown in Fig. 334. The strings are fastened to

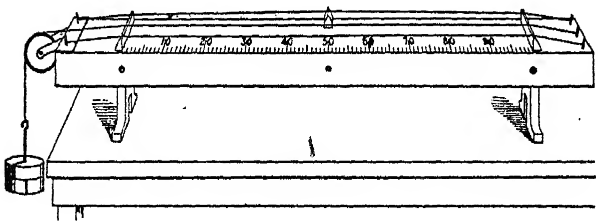


FIG. 334.—A sonometer, consisting of stretched strings over a thin wooden box. By means of a bridge we can use any part of a string.

steel pins near the ends of the instrument, and then pass over fixed bridges near them. The tension of a string can be altered by turning the pins with a key, or we may pass the string over a pulley and attach weights to its end. A movable bridge allows any portion of a string to be used.

The vibrations are produced by a bow, by plucking or by striking with a suitable hammer.

The thin wooden box which forms the body of the instrument strengthens the sound. If the ends of a string are fastened to massive supports, stone pillars for instance, it emits only a faint sound. Its surface is small and it can put in motion only a small mass of air. When stretched over the light box, however, the string communicates its motion to the bridges on which it rests, and these set up vibrations in the wooden box. The latter has a considerable surface and impresses its motion upon a large mass of air. In this way the volume of the sound is multiplied many times.

The motions which the bridges and the box undergo are said to be **forced** vibrations, while those of the string are called **free** vibrations.

322. Transverse Vibrations of a String—Law of Lengths. First, take away the movable bridge and pluck the string. It vibrates as a whole and gives out its **fundamental** note. Then place the bridge under the middle point of the string, and pluck again, thus setting one-half of the string in vibration. The note is now much higher and a trained ear will recognize it as the octave of the former note. We thus obtain *twice* the number of vibrations by taking *half* the length of the string.

For those who have difficulty in judging the octave it is better to proceed as follows:

First, remove the bridge and tune the string to unison with a 256-cycle tuning-fork by altering the tension. Then place the bridge under the string and hunt for a length which gives a note in unison with a 512-cycle fork. This length will be found to be one-half the former length. Similarly, if we find a length which gives the same note as a 320-cycle fork ($\frac{5}{4}$ of the original frequency), we discover that we are

using $\frac{4}{5}$ of the original length. Also $\frac{2}{3}$ of the string will be in unison with a 384-cycle fork which has $\frac{3}{2}$ the frequency of the original note.

If, further, we take lengths which are $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$ of the full length of the string, we secure six notes which, with the fundamental and its octave, comprise the major scale. Now from § 317 we see that the relative frequencies of the notes of the scale are proportional to the reciprocals of these fractions, and hence we deduce the

is—*The frequency of a string varies inversely as its length.*

323. Relation of Tension to Pitch. Upon altering the tension in a string, which we do by turning a key or by changing weights, we soon discover that an increase in the tension produces an increase in the frequency. To find the precise relation between frequency and tension we may use strings *A* and *B* on the sonometer, one string *B* having a hanger for weights or a spring balance attached to it so that we may know the tension.

Let us place a suitable weight on *B* and then alter the tension of *A* until it yields the same note as *B*. The tension of *A* is now kept constant for the remainder of the experiment.

Now we place the movable bridge under the middle of *A* in order to obtain a note which is the octave of that given by *B* and then let us keep adding to the weight on *B* until it gives a note in unison with this octave.

If the original tension was 5 pounds, the new tension will be 20 pounds, and we see that, in order to obtain twice the frequency, we have to multiply the tension 4 times. In order to obtain 3 times the frequency, we must multiply the tension 9 times; and so on. In this way we obtain the

Law of Tensions—*The frequency varies directly as the square of the tension.*

324. Laws of Diameters and Densities. Next, let us investigate the effect of using strings of different diameters. For this purpose we may use two strings of the same material, the same length and subjected to the same tension but one having twice the diameter of the other. We find that the frequency of the thicker string is only one-half that of the thinner. If the diameter is made three times as great, the frequency is reduced to one-third; and so on. In this way we obtain the

Law of Diameters—*The frequency varies inversely as the diameter of the string.*

On testing strings of different materials we reach the

Law of Densities—*The frequency varies inversely as the root of the density.*

Example. If we take wires of steel (s.g. 7·86) and of platinum (s.g. 21·50) of the same diameter, length and under the same tension, the number of vibrations of the steel wire will be $\sqrt{\frac{21\cdot50}{7\cdot86}} = 1\cdot65$ times that of the other.

325. Summary of Laws. It may assist the student to remember the laws of vibrating strings if he combines them in one statement as follows:

The frequency of a vibrating string varies inversely as
as the **square**
of the density and directly as **root of**
tension.

Examples. 1. A string 100 cm. long has a frequency of 320 v.p.s. when the tension is 16 pd. Find the frequency of the note emitted by 80 cm. of the same string when the tension is 9 pd.

Arrange the data in columns:

Frequency	*Length*	*Tension*
320 v.p.s.	100 cm.	16 pd.
?	80 cm.	9 pd.

New frequency = old frequency multiplied by corrections due to changes in length and tension.

(1) Since length is *decreased* the frequency will be *increased.*

New length = $\frac{80}{100}$ × original length.

Hence change in length would make new frequency $\frac{100}{80}$ × old frequency.

(2) Since tension is *decreased* the frequency will be *decreased.*

New tension = $\frac{9}{16}$ × original tension.

Hence change in tension would make new frequency $\sqrt{\frac{9}{16}}$ × old frequency.

Applying both of these corrections,

$$\text{New frequency} = 320 \times \frac{100}{80} \times \sqrt{\frac{9}{16}}$$
$$= 300 \text{ v.p.s.}$$

The steps labelled (1) and (2) will usually be performed mentally, thus shortening the solution.

2. A certain string has a frequency of 320 v.p.s. when the tension is 25 pd. Under what tension will it have a frequency of 256 v.p.s.?

Arrange the data in columns, representing the new tension by x.

Frequency	*Tension*
320 v.p.s.	25 pd.
256 v.p.s.	x pd.

New frequency = old frequency × correction for change in tension.

Hence 256 = 320 ×

from which $\frac{16}{25} = \frac{x}{25}$, and $x = 16$ pd.

The same procedure may be used in solving more complicated problems.

326. Nodes and Loops in a Vibrating String. The production of nodes and loops in a vibrating string can be beautifully exhibited on the sonometer (Fig. 335).

Experiment. Place five little paper riders on the wire at distances $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$ of the wire's length from one end. Then while a tip of the finger or a feather is gently held against the string at a distance $\frac{1}{4}$ of the length from the other end, carefully vibrate the string with a bow. The string will break up into nodes and loops, as shown

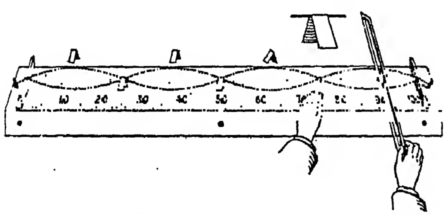


FIG. 335.—Obtaining nodes and loops in a vibrating string. The paper riders stay on at the nodes, but are thrown off at the loops.

in the figure, the little riders keeping their places at the nodes but being thrown off at the loops. The note emitted will be 2 octaves above the fundamental, with a frequency 4 times that of the latter.

In the same way, though somewhat more easily, the string can be made to break up into 2 or 3 segments. To obtain 2 segments, touch the string at the middle point; for 3 segments, touch it $\frac{1}{3}$ of the string's length from the end. In both cases, of course, the paper riders must be properly placed.

327. Simultaneous Production of Tones. When a string vibrates as a whole, as shown in (*a*), Fig. 336, it emits its fundamental tone. To emit its first harmonic or overtone it should assume the form shown in (*b*). In the same way the forms assumed when giving the higher overtones can easily be drawn.

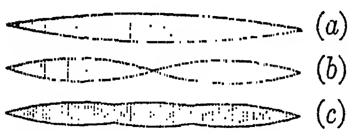


FIG. 336.—How a string vibrates when giving (*a*) its fundamental, (*b*) its first harmonic, (*c*) both of these together.

Now it is practically impossible to vibrate the string as a whole without, at the same time, having it divide and vibrate in segments. Thus with the fundamental tone of the string will be mingled its various harmonics.

The relative strengths of these harmonics will depend on the manner in which the string is put in vibration,—whether by a bow, by plucking or by striking it at some definite point. The sound usually described as "metallic" is due to the prominence of higher harmonics.

In (*c*), Fig. 336, is shown the actual shape of the string obtained by combining (*a*) and (*b*), that is, by adding the first harmonic to the fundamental.

The quality of a musical note depends on the presence of harmonics sounding with the fundamental. This will be discussed in greater detail in Chapter LI.

QUESTIONS AND PROBLEMS

(In the following problems "vibrations per second" is abbreviated to "v.p.s.").

1. Why is it advisable to strike a piano string near the end rather than at the middle?

2. A string 100 cm. long has a frequency of 200 v.p.s. Find the frequency of the note emitted by 80 cm. of the same string, if the tension remains constant. What length of the string would have a frequency of 300 v.p.s.?

3. A certain string has a frequency of 256 v.p.s. when the tension is 16 pd. Find the frequency when the tension is increased to 25 pd.

4. If the tension of a string emitting the note A is 25 pounds, find that required to produce C' whose frequency is $\frac{6}{5}$ that of A.

5. Two strings are of the same thickness and made of the same material. One is 10 in. long and has a tension of 9 pd.; the other is 12 in. long and has a tension of 16 pd. Compare the frequencies.

6. One wire is twice as long as another (of the same material and diameter), and its tension is 9 times as great. Compare the frequencies.

7. A string 1 m. long, stretched by a weight of 5 pd., gives a tone designated C. What must be the weight to give G? How much must the string under the original tension be shortened to give G?

8. Two steel strings have the same length and are subjected to equal tensions. The first has a diameter of 0·4 mm. and its frequency is 150 v.p.s. Find the frequency of the second whose diameter is 0·6 mm.

9. Two strings have equal lengths, diameters and tensions but the density of the second is $2\frac{1}{4}$ times that of the first. The frequency of the first is 90 v.p.s. Find the frequency of the second.

10. A steel wire 50 cm. long and under a tension of 6 pd., emits a note of 261 v.p.s. What must be the tension of the wire if its length be increased to 100 cm. and it yields a note one octave higher?

CHAPTER XLIX

VIBRATIONS OF PLATES AND RODS

328. Vibrations of Plates. The plates used in the study of sound are generally made of brass or glass, and are ordinarily square or circular in shape. The plate is held horizontally by a suitable clamp at its centre, and is made to vibrate by a violin bow drawn across the edge.

Let us scatter some sand over a square plate, and, while a finger-tip touches it at the middle of one side, draw the bow across the edge near one corner. At once a clear note is given, and the sand takes up the figure shown in *a*, Fig. 337. If the corner is damped with the finger-tip and the bow is applied at the middle of a side, the form shown in *b* is assumed, and the note is higher than the former. By damping with two finger-tips the form *c* is obtained and a much higher note is produced.

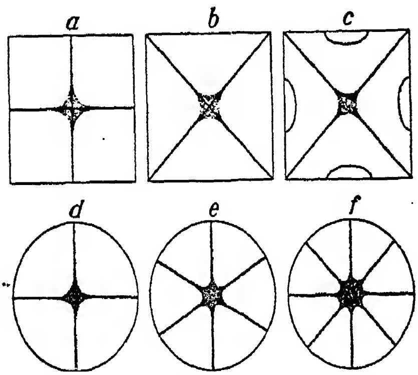


Fig. 337.—Sand-figures showing nodal lines in vibrating plates.

The sand is tossed away from certain parts of the surface and collects along the **nodal** lines, that is, those portions which are at rest.

Some of the forms assumed by the sand when a circular plate is vibrated are shown in *d*, *e*, *f*. The sand-figures always reveal the character of the vibration, and the more complicated the figure, the higher pitched the note.

329. Vibrations of Rods. The vibration of a rod clamped at its middle and stroked longitudinally has been described in § 300, in connection with Kundt's tube.

But a rod may vibrate transversely also. Let it be clamped at one end and the other end be drawn aside and let go. Ordinarily it will vibrate as in *a*, Fig. 338, in which case it produces its fundamental tone. But it may vibrate as illustrated in *b* and *c*, emitting its overtones.

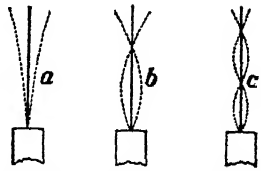


FIG. 338.—Vibrations of a rod clamped at one end.

The vibrations are due to the elasticity of the rod. The investigation of these transverse vibrations is somewhat complicated and difficult, but it is easy to demonstrate that an increase in length lowers the frequency and that an increase in thickness raises the frequency. The actual law is as follows:

Law of Transverse Vibrations of Rods—*The number of vibrations per second varies inversely as the square of the length of the rod and directly as its thickness.*

Example. A dinner gong composed of four tubes tuned to give a musical chord illustrates well the law of transverse vibrations of rods and can easily be made. Brass tubing about $\frac{3}{4}$ inch in diameter is suitable. Suppose we wish the tubes to give the notes *C*, *E*, *G*, *C′* of the diatonic scale (§ 315), the frequencies of which are proportional to 4, 5, 6, 8, respectively. The thickness (diameter) of the tubes is the same and so need not be taken into account. Let the length of the longest tube (*C*) be 18 inches and that of the next (*E*) be x inches. Then the above law says that the frequency of *C* is to the frequency of *E* inversely as the square of 18 is to the square of x, or, in symbols, $\frac{4}{5} = \left(\frac{x}{18}\right)^2$, from which $x = 16{\cdot}1$ inches.

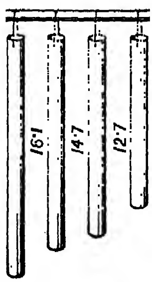


FIG. 338a.—A dinner gong.

Similarly the lengths of the *G* and *C′* tubes are found to be 14·7 and 12·7 inches, respectively.

Make the tubes of these lengths and suspend them by cords through holes near one end, as in *a*, Fig. 338. Strike with a wooden or rubber hammer and they will give the major tetrad.

In place of tubes metal bars may be used.

330. Tuning-Fork. A tuning-fork may be considered as a rod which is bent and held at its middle point. When it vibrates, the two prongs alternately approach and recede, while the stem has a slight motion up and down. Why this is so may be seen from Fig. 339. In 1, *N*, *N* represents the nodes when the straight bar is made to vibrate. As the bar is bent more and more, the nodes approach the centre, and when the fork is obtained (as in 2), the nodes are so close together that the motion of the stem is very small. That it exists, however, can be readily shown.

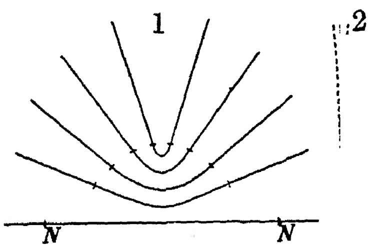


FIG. 339.—How a tuning-fork vibrates.

If a fork, after being set in vibration, is held in the hand, it will continue in motion for a long time. It gives up its energy slowly, and so the sound is feeble. But if the stem is pressed against the table, the sound is much louder. Here the stem produces forced vibrations in the table, and a large mass of air is thus put in motion. In this case the energy of the fork is used up rapidly and the sound soon dies away.

Tuning-forks are of great importance in the study of sound. When set in motion by gentle bowing, the overtones, if present at all, die away very rapidly.

With a rise in temperature the elasticity of the steel is diminished and the pitch is slightly lowered.

From our consideration of the law of vibrating rods we should naturally conclude that shortening the prongs of a fork would raise the frequency and that making the prongs thinner would lower the frequency. This is verified by trial.

QUESTIONS

1. Name some musical instruments in which the transverse vibrations of rods or strips are utilized.

2. Using diagrams, describe how a rod clamped at one end vibrates when it is emitting its fundamental tone and also when producing its first and second overtones.

3. Describe how a tuning-fork vibrates. How would you demonstrate that the handle is in a state of vibration when the fork is sounding?

4. A tuning-fork which is supposed to have a frequency of 256 v.p.s. is found to have a frequency of only 250. How could you raise the frequency? What change would you make in a fork to lower its frequency slightly?

5. Make diagrams showing three different ways in which, (1) a square plate, (2) a circular plate, may vibrate when clamped at the centre. Explain how you would produce these states of vibration.

REFERENCES FOR FURTHER INFORMATION

TYNDALL, *Sound*, Chapters 3, 4, 5.
CATCHPOOL, *Text-Book of Sound*, Chapters 11, 12.
POYNTING AND THOMSON, *Sound*, Chapters 6, 7, 8.
MILLER, *The Science of Musical Sounds*.

CHAPTER L

VIBRATIONS OF AIR COLUMNS; ORGAN PIPES

331. Vibrations of Air Columns; Resonance. Let us support a tube about 2 inches in diameter and 18 inches long with its lower end in a vessel containing water (Fig. 340); and over the open end hold a vibrating tuning-fork. Suppose the fork to make 256 vibrations per second.

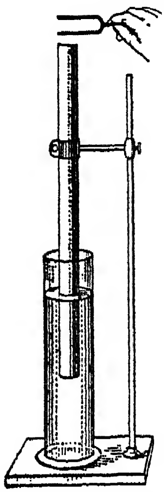


FIG. 340.—Air column in resonance with a tuning-fork.

By moving the tube up and down we find that, when it is at a certain depth, the sound we hear is greatly intensified. This is due to the air column above the water in the tube. It must have a definite length for each fork. On measuring it for this one we find it is approximately 13 inches. With higher pitched forks it is shorter than this, being always inversely proportional to the frequency of the fork.

The air column is put in vibration by the fork, its period of free vibration being the same as that of the fork. The air column is said to be in resonance with the fork.

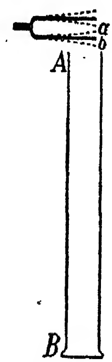


FIG. 341.—Diagram to explain resonance in a closed tube.

332. Explanation of the Resonance of the Air Column. The tuning-fork prong vibrates between the limits *a* and *b* (Fig. 341). As it moves forward from *a* to *b*, it produces a condensation which runs down the tube and is reflected from the bottom. When the fork retreats from *b* to *a*, a rarefaction is produced, which also travels down the tube and is reflected.

Now for resonance the tube must have such a length that in the time that the prong moves from a to b the condensation travels down the tube, is reflected, and arrives back at b just in time to add its effect to the condensation which starts in an upward direction as the prong moves from b to a. Moreover, as the condensation leaves the tube a rarefaction starts down the tube exactly in step with the rarefaction now being sent out from the prong in this downward direction. Thus the vibrations of the fork and of the air column are perfectly synchronous; and as the fork continues to vibrate, the motion of the air in the tube becomes greater and spreads in the room, producing the marked increase of sound.

333. Determination of the Velocity of Sound by Resonance. From the explanation given of the resonance of the air column in a tube, it is seen that the sound-waves travel down the tube and back again while the fork is making half of a complete vibration or cycle. During a complete cycle the waves will travel *four* times the length of the air column; but we know that while the fork performs a cycle the sound-waves travel a wave-length. Thus the length of the air . is one-fourth of a wave-length of the sound emitted fork.*

If we know the frequency of the fork, we can, by measuring the length of the resonance column, at once deduce the velocity of sound. Also, if we know the length of the resonance column and the velocity of sound, we can deduce the pitch.

Example. Using the values given in § 333, find the velocity of sound.
Frequency $n = 256$ per sec.; wave-length $l = 4 \times 13 = 52$ in.
Hence $v = nl = 256 \times 52$ in., or $1109\frac{1}{3}$ ft., per sec.

34. Forms of Resonators. A resonator is a hollow vessel tuned to respond to a certain definite pitch. Two forms are

*More accurately the quarter wave-length of the sound is equal to the distance from the surface of the water to the top of the tube + 0·4 of the diameter of the tube.

shown in Fig. 342. In each case there is a larger opening, which is placed near the source of the sound, while the smaller opening is either placed in the ear, or a rubber tube leads from it to the ear. The volume is carefully adjusted so as to be in resonance with a tuning-fork (or other body) vibrating a definite number of times per second.

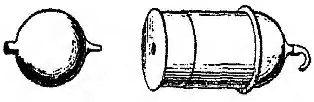


FIG. 342.—Two forms of resonators. The one on the right can be adjusted for different tones.

These resonators are used to analyse a compound note. We can test whether there is present a tone corresponding to that of the resonator, by simply holding the instrument near the sounding body; if the air in the resonator responds, that tone is present, if it does not respond, the tone is absent.

The spherical form was used largely by the great German scientist Helmholtz; the other, which can be adjusted to several tones, was introduced by Koenig. They are usually made of glass or brass, but quite serviceable ones can be made in cylindrical shape out of heavy paper. (See also §§ 346, 353.)

Tuning-forks which are used in acoustics are generally mounted on a light box of definite size (see Fig. 352). This is so constructed that the air within it is in resonance with the fork. The air within vibrates naturally in the same period as the fork. If a fork is held with its stem resting on the table, the table is *forced* to vibrate in consonance with the fork.

335. Resonance of an Open Tube. Let us take two tubes, about $1\frac{1}{2}$ inches in diameter, one slipping closely over the other. Each may be 15 or 18 inches long (Fig. 343). Now vibrate the fork whose frequency is 256 per second and hold it close to one end of the tube, varying the length at the same time.

FIG. 343.—The length of an open tube when in resonance with a tuning-fork is one-half the wave-length of the sound.

At a definite length the air within the tube vigorously responds, and there is a marked increase in the sound. On measuring the length of the tube we find it is 26 inches, just twice the length of the tube which responded when one end was closed.

But we found that the closed tube was one-fourth the wave-length of the sound to which it responded; hence an open tube is one-half the wave-length of the sound given by it.

The relation between the notes emitted by an open and a closed pipe of the same length can easily be illustrated by blowing across the end of a tube (say $\frac{1}{2}$ inch in diameter and 2 inches long), and observing the note produced when the tube is open and when a finger is held over one end of it. The former note is an octave higher than the latter.

Why should an open tube respond to the tuning fork? In the case of a closed tube we saw that condensations and rarefactions were reflected from the closed end of the tube as condensations and rarefactions; but, when a condensation comes to the open end of a tube it passes out and a rarefaction is "reflected" back. (A condensation represents air under pressure greater than normal and the rarefaction is produced by the sudden expansion of this air when it arrives at the open end). Similarly, a rarefaction is reflected from the open end as a condensation. Consequently for resonance the prong must make a complete vibration while the sound travels twice the length of the tube.

336. Mode of Vibration in an Open Tube. When a rod is clamped at the middle and one half is stroked, as in § 300, both halves lengthen and shorten.

Fig. 344.—Expl ing h 1 open pipe vibra

There is a node at the middle, which is always at rest, and a loop at each end.

The air in an open tube vibrates quite similarly; indeed, it behaves like two closed tubes placed end to end. (Fig. 344).

The layer of air across the middle of the open tube remains at rest while those on each side of it crowd up to it and then separate from it again. The layers at either end swing back and forth, without appreciably approaching those next to them.

There is the greatest change of density at the middle of the open tube, or the bottom of the closed tube,—that is, at the node,—while the air particles execute the greatest swing back and forth (without change in the density of the air) at the open ends. There is a loop at each end.

Now the distance from a loop to a node is one-quarter of a wave-length and from a loop to a loop is one-half of a wave-length. Hence in the simplest state of vibration the wave-length of the note emitted by a closed tube is four times its length and by an open tube is twice its length.

Exercise. Obtain four glass or tin tubes having lengths 30, 24, 20, 15 cm. and blow across the end of each in succession,—first, with both ends open; second, with one end closed. Describe what you hear.

QUESTIONS AND PROBLEMS

1. Explain how you would demonstrate the phenomenon of resonance, (*a*) with a closed tube, (*b*) with an open tube.

2. As water is poured into a deep bottle the sound rises in pitch. Explain why.

3. At a certain temperature a tube, closed at one end and 10·25 in. long, is found to be in resonance with a fork whose frequency is 320 v.p.s. Find the velocity of sound in air in feet per second.

4. Find in inches the lengths of the shortest closed pipe and of the shortest open pipe which would respond to a tuning-fork making 256 vibrations per second. (Temperature 20° C.)

5. Find in inches the length of an air column in resonance with a 320-cycle fork at 15° C.

337. Organ Pipes. The most familiar application of the vibrations of air columns is in organ pipes. They are made either of wood or of metal. If of wood, pine, cedar or mahogany is used; if of metal, tin (with some lead in it) or zinc.

In Fig. 345 is shown a lengthwise section of a wooden pipe of square cross-section, and in Fig. 346 is the mouth-end of such a pipe with some difference in detail. In Fig 347 is a metallic pipe. This one is cylindrical in form but some pipes are conical in shape.

FIG. 345.—Section of a wooden organ pipe.

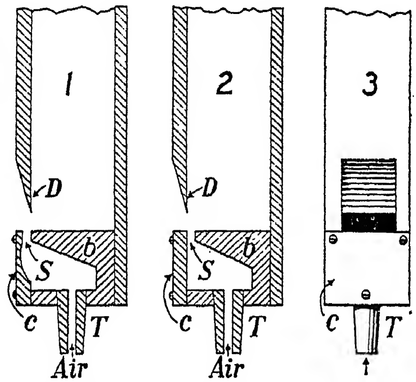


FIG. 346.—Section of the mouth end of two types of pipes. In (1) the windway S is cut from the cap c; in (2) it is cut from the block b. In (3) is a front view.

FIG. 347.—A metallic organ pipe.

Air is blown through the mouthpiece T and emerges through the slit S where it strikes the lip D and is divided. By this action a periodic variation in the pressure in the air is set up. The air alternately passes inside and outside through the slit, and pulses are produced which travel up and down the pipe. The vibration frequency depends on the length of the pipe, as it does in resonance, but here there is no fork or other vibrating solid body to set the air in motion. The length of the air column determines its frequency.

Organ pipes are of two kinds, open and closed. In some open pipes reeds are used (§ 351). When emitting its fundamental note a closed pipe has a node at the closed end and a loop at the open end; an open pipe has a loop at each end and a node in the middle as in Fig. 344.

Consider now an open pipe and a closed pipe of the same length d. The wave-length of the note given by the open

pipe is $2d$, that given by the closed pipe is $4d$; or the wave-length given by the open pipe is one-half that given by the closed pipe; and hence **the note emitted by an open pipe is an octave above that emitted by a closed pipe of the same length.**

338. Overtones (or Harmonics) in an Organ Pipe. The vibrations of the open and closed pipes which have been described in §§ 331-336, are the simplest which the air column can make, and they give rise to the lowest or fundamental notes of the pipes. In order to obtain the fundamental the pipe must be blown gently. If the strength of the air current is gradually increased, other tones, namely, the overtones of the pipe, will also be heard.

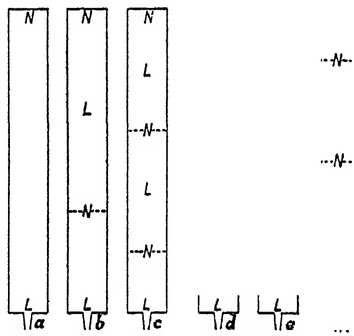
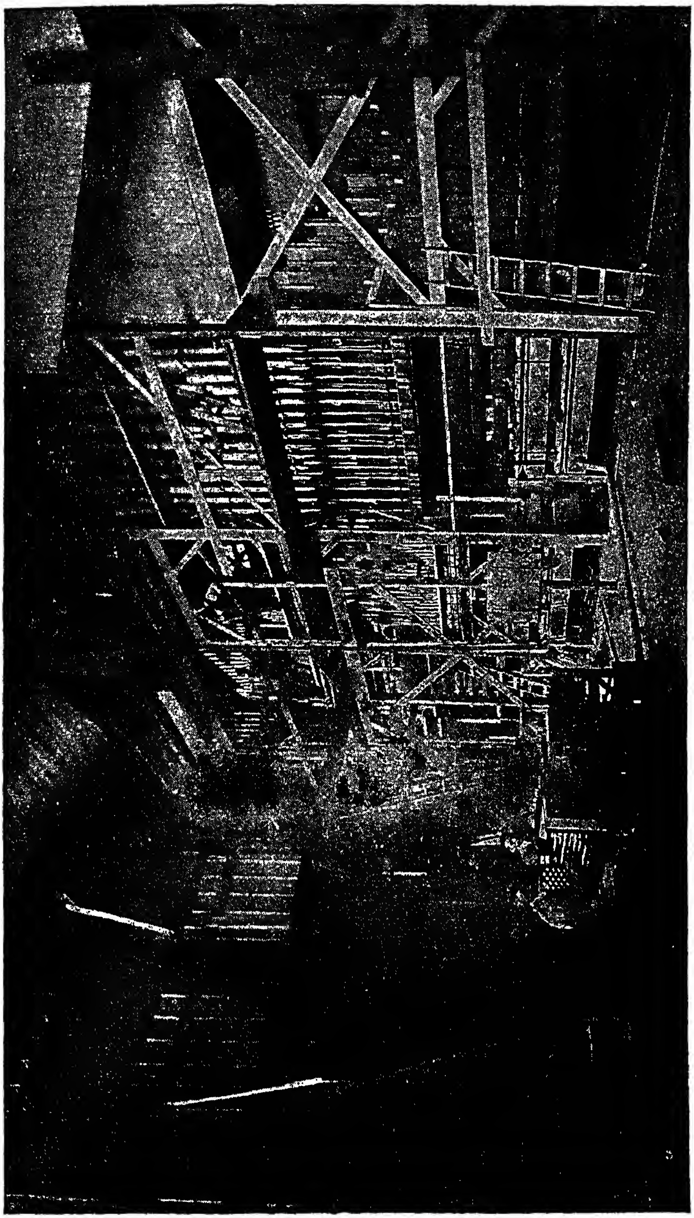


FIG. 348.—Showing the nodes and loops in open and closed organ pipes with different strengths of air currents.

In a, b, c, Fig. 348, are represented the divisions of the air column in a stopped pipe corresponding to different strengths of the air current. In a we have the fundamental vibration; here the column is undivided. The only node present is at the closed end, and there is a loop at the lip end. In b is shown the condition of the air column corresponding to the first overtone of the pipe. There is a node at the closed end, and another at a distance $\frac{1}{3}$ of the length of the pipe from the lip end. Thus the distance from a node to a loop is $\frac{1}{3}$ that in a, and the wave-length of the note is $\frac{1}{3}$ that of the fundamental. Its frequency is 3 times that of the fundamental.

In c there are three nodes and three loops, in the places indicated. From a node to a loop the distance is $\frac{1}{5}$ of the



REGULATING THE PIPES OF A LARGE CANADIAN ORGAN

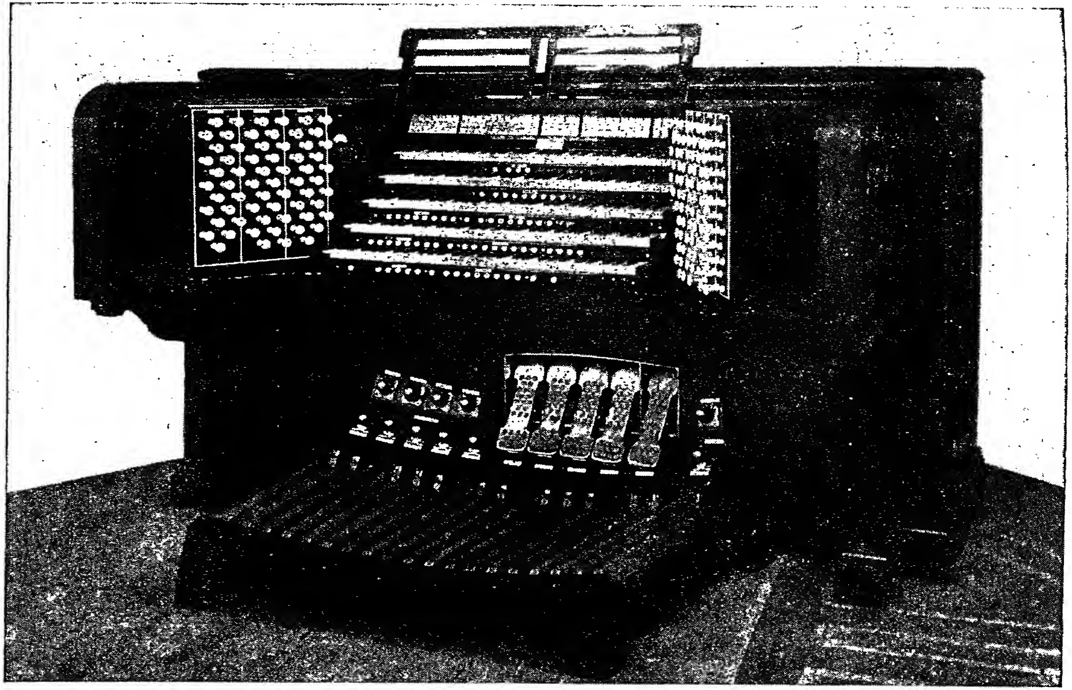
● **Plate 26**

The above photograph shows the pipes of a large four-manual organ as they are being regulated in the factory. Many pipes, wind reservoirs and other parts cannot be seen in the picture. The stairs at the left are only temporary.

The pipes vary greatly in size. In the four-manual organ in Convocation Hall, Toronto, there are 5,092 speaking pipes. The largest wooden pipe is 2 ft. 4 in. by 2 ft. 1 in. in section and 32 ft. long, made from 2-inch lumber. The smallest one is ¾ in. square and 3 in. long, the lumber being ⅛ in. thick. The largest metal pipe is 10 in. in diameter and 16 ft. long while the smallest is 3/16 in. in diameter and ½ in. long.

The organ of the Metropolitan Church, Toronto, has 5 manuals and 7,784 speaking pipes; while St. Paul's Anglican Church has 7,368 speaking pipes.

(Photograph from Casavant Frères.
St. Hyacinthe, Que.)



CONSOLE OF THE ORGAN IN THE METROPOLITAN CHURCH, TORONTO

This is the largest organ in Canada. (Photograph from Casavant Frères, St. Hyacinthe, Que.)

length of the pipe, and hence the wave-length of the sound is $\frac{1}{5}$ and its frequency 5 times that of the fundamental. The succeeding harmonics produced would have frequencies 7, 9, . . . times that of the fundamental. Thus we see that in a closed pipe only the harmonics having frequencies an odd number of times that of the fundamental are present.

Next consider the open pipe (*d*, *e*, *f*, Fig. 348). For the fundamental the air column divides as shown in *d*, with a node at the middle and a loop at each end. With stronger blowing there is a loop at the middle as well as at each end and nodes half-way between as in *e*. In this case the wave-length is $\frac{1}{2}$ and the frequency twice that of the fundamental.

In *f* is shown the next mode of division of the air column. It will be seen that the wave-length is $\frac{1}{3}$ and the frequency 3 times that of the fundamental. By using still stronger currents of air we get harmonics with frequencies 4, 5, 6, ... times that of the fundamental. Thus in an open pipe all the harmonics (or overtones) can be produced.

From this discussion we see that, although an open organ pipe will give the same fundamental note as a closed one of one-half the length, the note emitted by the open pipe will be richer in overtones and will have a different quality. Consequently both kinds of pipe are used in organs.

QUESTIONS AND PROBLEMS

1. Make diagrams showing three different ways in which, (*a*) a closed organ pipe, (*b*) an open organ pipe of the same length, may vibrate.

2. If the frequency of the fundamental note of the closed pipe in Question 1 is 100 v.p.s., calculate the frequencies of the other two notes.

3. Why are both open and closed pipes used in pipe-organs?

4. What effect will a rise in temperature have on the notes of a pipe organ?

5. Find the length of a stopped pipe whose fundamental has a frequency of 522. (Temperature, 20° C.)

6. An open pipe 6 ft. long produces a note of frequency 256. What must be the length of a closed pipe which produces a note of frequency 512?

7. A stopped pipe is 4 feet long and an open one 12 feet long. Compare the pitch and the quality of the two pipes.

8. Let v be the velocity of sound in air and n_1, l_1 be the frequency and wave-length of the note emitted by an open pipe of length d; also let n_2, l_2 be the frequency and wave-length of the note emitted by a closed pipe of the same length: then use the relation $v = nl$ (§ 294) to compare n_1 and n_2.

9. What would be the effect on an organ pipe if it were filled with carbon dioxide gas? What with hydrogen? (See § 301.)

10. Use the equation $v = nl$ to find the vibration frequency of the note emitted by an open pipe of length 5 ft. if it were filled with air, carbon dioxide, hydrogen, the velocity of sound in these gases being taken to be 1090, 860, 4200 ft. per sec., respectively.

CHAPTER LI

QUALITY, VIBRATING FLAMES, BEATS

339. Quality of Sound. It is a familiar and remarkable fact that though sounds having the same pitch and intensity may be produced on the piano, the organ, the cornet, or with the human voice, the source of the sound in each case can be easily recognized. That peculiarity of sound which allows us to make this distinction is called **quality.**

The cause of this was not explained until Helmholtz showed that it depends on the co-existence with the fundamental of secondary vibrations which alter the forms of the sound waves. These secondary vibrations are the overtones or harmonics, and their number and prominence determine the peculiar characteristics of a note.

In general, those notes in which the fundamental is relatively strong and the overtones few and feeble are said to be of a "mellow" character; but when the overtones are numerous, the note is harsher and has a so-called metallic sound. If a musical string is struck with a hard body, the high harmonics come out prominently.

When a violin string is bowed, the first seven overtones are present, and give to the sound its piercing character. In the case of the piano the 1st, 2nd and 3rd overtones are fairly strong while the 4th, 5th and 6th are more feeble.

340. Vibrating Flames. The cause of quality was investigated by Helmholtz by means of spherical resonators (Fig. 342). But a very beautiful and simple way of investigating the complex nature of sound waves is by means of the manometric, or "pressure-measuring," flame devised by Koenig.

A convenient form of the apparatus is shown in Fig. 349. A small chamber is divided into two compartments by a

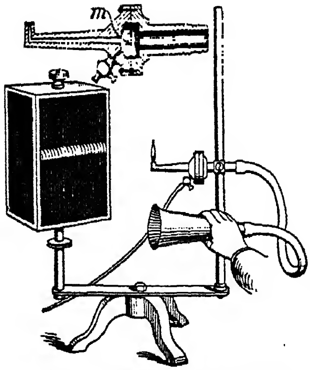


FIG. 349.—The manometric flame and mirror. A section of the gas chamber is shown separately above. On speaking into the funnel the flame dances rapidly up and down, and this motion is observed in the square mirror which is rotated by hand.

membrane m, made of very thin mica or rubber. Gas enters one compartment, as shown in the figure, and is lighted on leaving by a fine tip. The other compartment is connected by a rubber tube with a funnel-shaped mouth-piece.

The sound waves enter the funnel, and their condensations and rarefactions produce variations in the density of the air beside the membrane. This makes the membrane vibrate back and forth, and the gas flame dances up and down. But these motions are so rapid that the eye cannot follow them, and in order to separate them they are viewed by reflection in a rotating mirror.

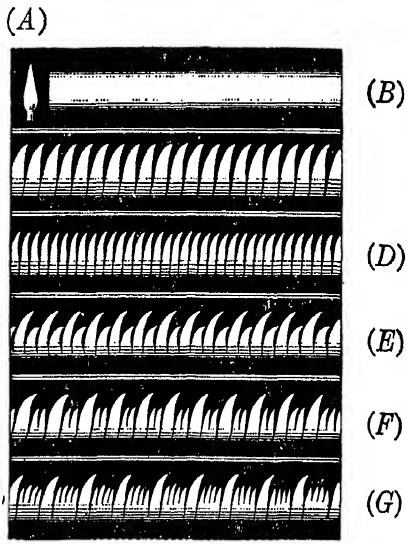


FIG. 350.—Flame pictures seen in the rotating mirror. *A*, when mirror is at rest; *B*, when flame is at rest and mirror rotating; *C*, when a tuning-fork is held before the mouthpiece; *D*, same as *C* but an octave higher; *E*, when *C* and *D* are combined; *F*, obtained with vowel *e* at pitch *C′*; *G*, with vowel *ō* (as in *so*) at the same pitch.

The appearance of various images of the flame is given in Fig. 350. When the mirror is at rest, the image is seen as at *A*. If now the mirror is rotated while the flame is still, the image is a band of light, *B*. If one sings into the conical mouthpiece the sound of *oo* as in *tool*, or if one holds before it a vibrating mounted tuning-fork the gas-jet's motion appears in the mirror like *C*. If

the note is sung an octave higher, there will be twice as many little tongues in the same space, *D*. When these two tones are sung together, images as in *E* are given. On singing the vowel *e* at the pitch C' we obtain images as at *F*; and *G* is obtained on singing ō at the same pitch.

From the figures it will be seen that the last three notes are complex sounds. These dancing images have been successfully photographed on a moving film.

A simple form of the above apparatus can be constructed by anyone (Fig. 351). Hollow out a piece of wood or cork (2 inches in diameter), *A*, and across the opening stretch the membrane, *M*, keeping it in place by screwing or pinning a ring *B* against it. Gas enters by the tube *C* and leaves by the tube *D*. No mouthpiece is necessary, but a funnel, shaped as shown in the dotted line, will increase the effect. In place of the rotating mirror a piece of mirror 6 or 8 inches square, held in the hand almost vertical and given a gentle oscillatory motion will good results.

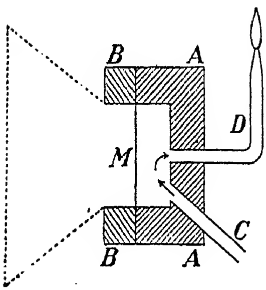


Fig. 351.—A simple form of manometric flame capsule. *AA* is a cork hollowed out, *M* is the thin membrane.

341. Sympathetic Vibrations. Place two tuning-forks which have the same vibration number, with the open ends of their resonance boxes facing each other and a short distance apart (Fig. 352). Now vibrate one of them vigorously by means of a bow or by striking with a soft mallet (a rubber stopper on a handle), and, after it has been sounding for a few seconds, bring it to rest by placing the hand upon it. The sound will still be heard, but on examination it will be found to proceed from the other fork.

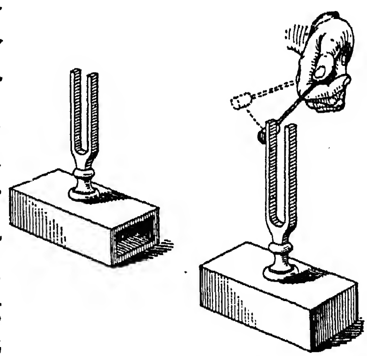


Fig. 352.—Two tuning-forks arranged to show sympathetic vibrations. When one is vibrated the other responds.

This illustrates the phenomenon of sympathetic vibrations. The first fork sets up vibrations in the resonance box on which it is mounted, and these produce vibrations in the inclosed air column. The waves proceed from it, and, on reaching the resonance box of the second fork, put its air column in vibration. The vibrations are communicated to the box and then to the fork, which, having considerable mass, continues its motion for some time.

A single wave from the first fork would have little effect, but when a long series comes in regular succession, each helps on the action of the one next before it. Thus the effect accumulates until the second fork is given considerable motion, its sound being heard over a large room.

For the success of this experiment the vibration numbers of the two forks must be accurately equal.

342. Illustrations of Sympathetic Vibrations. The pendulum of a clock has a natural period of vibration, depending on its length. If started, it continues swinging for a while, but at last it comes to rest. Now the works of the clock are so constructed that a little push is given to the pendulum at each swing, and these pushes, being properly timed, are sufficient to keep up the motion.

Again, it is impossible by a single pull on the rope to ring a large bell, but if one times the pulls to the natural period of the bell's motion, its amplitude continually increases until it rings properly. In the same way a heavy swing, may be put in motion.

When soldiers are crossing a suspension bridge they are usually made to break step for fear that the steady tramp of the men might start a vibration agreeing with the free period of the bridge, and this vibration, by continual additions, might reach dangerous proportions.

343. Beats. We shall experiment further with the two unison forks (Fig. 352). Stick a piece of wax* on each prong of one fork; we cannot get sympathetic vibrations now, but on vibrating the two forks at the same time we hear a peculiar wavy or throbbing sound, caused by alternate rising and sinking in loudness. Each recurrence of maximum loudness is called a **beat**.

We at once recognize that this effect is due to the interaction of the waves from the two forks, resulting in an alternate increase and decrease in the loudness of the sound.

Each fork produces condensations and rarefactions in the air, and since a condensation on reaching the ear would tend to push the ear-drum in, while a rarefaction would cause it to move out, it is evident that if a condensation from one fork reaches the ear at the same time as a rarefaction from the other, they will oppose their effects, and the ear-drum will have little motion—the sound will be faint. If, however, a condensation from each or a rarefaction from each arrives at the same time, the action on the ear-drum will be increased and the sound will be louder.

Now if one fork makes 256 vibrations per second and the other 250, the former of course makes 6 vibrations per second more than the latter. Hence it would appear that the two forks should be exactly in phase (both sending out condensations or rarefactions at the same time) 6 times per second and that they should be vibrating in opposite phases 6 times per second. The number of beats per second should therefore be 6 which is the difference in the frequencies. This is discussed from a different standpoint in the next section.

344. Number of Beats per Second. For simplicity, let us suppose that we have two rods held at the lower end and vibrating transversely, one of them having a frequency of 4 and the other of 5

*The soft modelling wax sold as "plasticine" is very convenient.

vibrations per second. If they start vibrating in the same direction at the same time, the conditions after one second will be as shown in Fig. 353, in which lines close together represent a condensation and lines far apart a rarefaction.

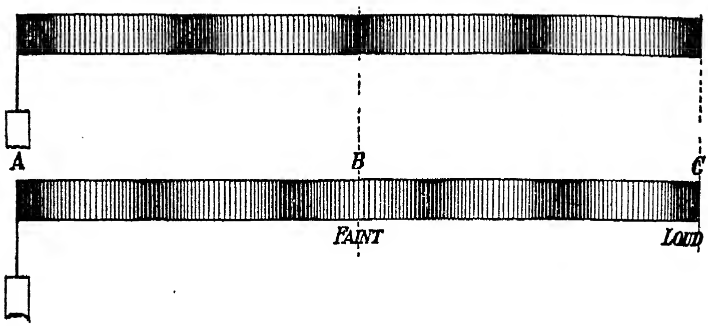


FIG. 353.—Illustrating the production of beats. Two condensations or two rarefactions coming together strengthen each other. A condensation and a rarefaction destroy each other's effect.

The distance AC, traversed by the sound in one second, will be 1120 ft., and it is equal to 4 wave-lengths of the motion from the first rod and 5 wave-lengths from the second rod.

Suppose one person is stationed at B and another at C. From the diagram it is evident that the person at C is receiving a condensation from each rod and, consequently, hears a loud sound. At the same time the person at B is receiving a condensation from the first rod and a rarefaction from the second and hence hears a faint sound.

But the sound pulses keep travelling towards the right, and the condition which exists at B now will be at C one half second later, and after still another half second the two pulses of condensation just starting from A will arrive at C. Thus there will be *one* beat per second.

From a similar diagram drawn for rods vibrating 4 and 6 times per second it will be seen that in this case there would be *two* beats per second.

Now we cannot hear notes whose frequencies are 4 and 5 vibrations per second but we can if the frequencies are 40 and 50 vibrations per second or 4 and 5 in one-tenth of a second. In this case there would be one beat in each one-tenth second or ten beats per second.

We arrive, then, at the simple law that **the number of beats per second due to two simple tones is equal to the difference of their respective vibration numbers.**

To produce beats the forks should not differ greatly in pitch.

We may utilize beats for tuning. Suppose we wish to tune two strings to unison. Even the most unmusical person can do it. Simply vary the tension, or the length, of one of them until, as they approach unison, the beats are fewer per second. If one beat per second is heard, there is a difference of only one vibration per second in their frequencies. Let us alter a little more until the beats are entirely gone. The strings are then in unison.

In the same way other sounding bodies, for instance two organ pipes, or a pipe and a tuning-fork, may be brought to unison.

345. Interference of Sound waves. The production of beats is but one of the many phenomena due to the interference of sound waves. Let us consider two other examples.

In Fig. 354 are shown the ends of the two prongs of a tuning-fork. They vibrate in such a way that they move alternately toward and away from each other. Thus while they produce a condensation in the space *a* between them, they produce a rarefaction at *b* and *c* on the opposite sides. In this way each prong starts out two sets of waves, which are in opposite phases. These waves travel out in all directions, and it is evident that we can find points such that when the two sets of waves arrive at them they will be in opposite phases and so will counteract each other's effects. Such points are located on two curved surfaces, of which *fg*, *hk* are horizontal sections.

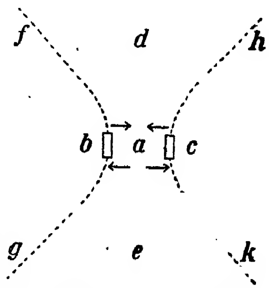


FIG. 354.—Interference with a tuning-fork.

This can be demonstrated by holding a vibrating fork near the ear and then rotating it slowly. When the ear is in the positions *b*, *c*, *d*, *e*, the sound is heard clearly; while if it is on either of the curved surfaces *fg*, *hk* no sound is heard.

Also if the fork is held horizontally over the mouth of a resonator and rotated slowly the positions of least intensity of sound may be demonstrated to a whole class.

346. Interference with Resonators. Another interesting experiment can be performed with simple means.

Experiment. Procure two wide-mouthed bottles as in Fig. 355. Vibrate a tuning-fork (256 vibrations) over the mouth of one of the bottles, and slip a microscope slide over the mouth until the air in the bottle responds vigorously. Fasten with wax the glass in the position when

the bottle resounds most loudly. The bottle is then a resonator tuned to the fork.

Tune the other bottle in the same way, and then arrange them, with their mouths close together, as shown in the figure. Make the fork vibrate, and then, holding it horizontally, bring it down so that the space between the prongs is opposite the mouth of the upright bottle. As it is brought into place observe that the sound first increases, and then suddenly fades away or disappears entirely.

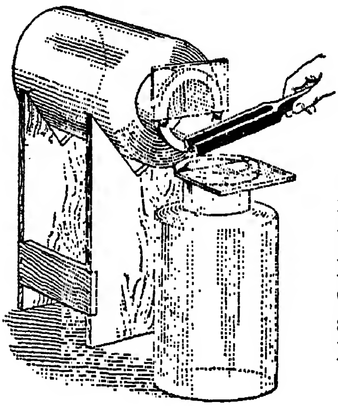


Fig. 355.—Interference with two resonators.

The reason for this is easily understood. The air in one bottle is put in vibration by the air from between the prongs, while that in the other is put in vibration by the air on the other side of the prongs; and these, as we have seen, are in opposite phases. Hence they interfere and produce silence.

If a card is slipped over the mouth of one of the bottles, that bottle's vibrations are shut off and the other sings out loudly.

347. Doppler's Principle. Suppose a body at A to be emitting a note of n vibrations per second. Waves will be excited in the surrounding air, and an observer at B will receive n waves each second. He will recognize a sound of a certain pitch.

Next, suppose that the observer approaches the sounding body; he will now receive more than n waves in a second. In addition to the n waves which he would receive if he were stationary, he will meet each second a certain number of waves, since he is nearer the sounding body at the end of a second than he was at its beginning. He will receive those waves which at the commencement of the second occupied the space he has moved. As he will now receive more than n waves per second, the pitch of the sound will appear to be higher than when there was no motion.

If the observer moves away, the number of waves received will be smaller and the pitch will be lowered.

If the observer remains at rest while the sounding body approaches or recedes, similar results will be obtained; and if we can determine the change in pitch, we can calculate the speed of the motion. This phenomenon is known as the Doppler effect, and the explanation given is known as Doppler's Principle.

The Doppler effect can be observed when a whistling locomotive is approaching or receding at a rapid rate. An automobile sounding its horn is a still better illustration as its motion makes less noise. When the machine is approaching, the sound is distinctly higher in pitch than when it is travelling away.

QUESTIONS AND PROBLEMS

1. Explain what is meant by the *quality* of a musical note. How does it differ from *pitch* and *intensity*?

2. If one presses the loud pedal of a piano and then sings into the piano a sound will sometimes be heard after the singing has ceased. Why?

3. A tuning-fork on a resonance box is moved towards a wall, and a 'wavy' sound is heard. Explain the production of this.

4. Hold down two adjacent bass keys of a piano. Count the beats per second and deduce the difference of the vibration numbers.

5. A tuning-fork whose frequency is 512 v.p.s. is sounded with a second fork and it is observed that there are 36 beats in 12 seconds. Find the frequency of the second fork. How could you determine which of the two possible results is the correct one?

6. If a circular plate is made to vibrate in four sectors as in *d*, Fig. 337, and if a cone-shaped funnel is connected with the ear by a rubber tube, and the other ear is stopped with soft wax, no sound is heard when the centre of the mouth of the cone is placed over the centre of the plate; but if it is moved outward along the middle of a vibrating sector, a sound is heard. Explain these results. (For a plate 6 inches in diameter the mouth of the funnel should be $2\frac{1}{2}$ inches in diameter. Try the experiment.)

7. A circular plate is made to vibrate in four sectors, and one ear (the other being covered over) is held directly over the centre of the plate at the distance of one foot or more. Little sound is heard. Why? From a circle of cardboard of the same size as the plate cut a pattern like that in *a*, Fig. 356, and having tacked this on the end of a light rod hold it over the vibrating plate and spin it round slowly. Describe the effect and account for it.

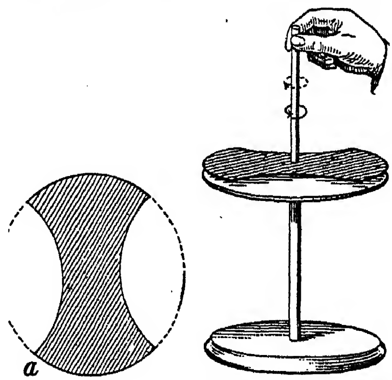


FIG. 356.

REFERENCES FOR FURTHER INFORMATION

Sound, Chapters 16 to 18. CATCHPOOL, *Sound*, Chapters 4, 8.

MILLER, *The Science of Musical Sounds*.

CHAPTER LII

MUSICAL INSTRUMENTS; THE PHONOGRAPH

348. The Human Voice. Among musical instruments we may well include the human voice. It is a remarkable feature of our wonderful body. The sound is produced by the edges of a pair of cartilaginous, or gristly, plates which form the cover of the voice box (or larynx) at the upper end of the windpipe. These edges are called the vocal cords. In breathing they are separated but in speaking or singing they are drawn together. When the air from the lungs is forced rapidly between them they vibrate and a note is emitted (Fig. 357).

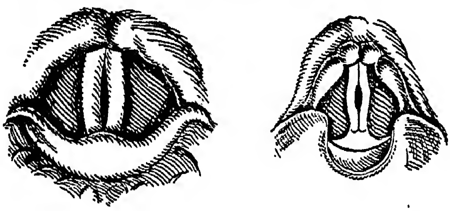


FIG. 357.—View, from above, of the vocal cords. On the left, the cords of a bass voice; on the right of a soprano as shortened to give a high note.

By means of the muscles of the throat (1) the tension on the vocal cords may be altered, and (2) their length may be changed. Thus the pitch of the note may be varied. The vibrations of the air surrounding the vocal cords are communicated to the air in the cavities of the throat, nose and mouth, and these modulate the original sound. The quality of the sound depends greatly on these cavities. The notes produced are very complex, consisting of a fundamental with many harmonics.

Our speech is made up of vowels and consonants. The vowels are produced in the voice box, the consonants in the mouth. Whistling and whispering are caused by lip vibrations.

In recent years methods have been devised for measuring the mechanical power used in speech. It is extremely small. As an illustration, it has been shown that if the energy required for speech could be used to boil

water, 1000 people would have to talk continuously for three hours in order to give enough energy to heat a cup of tea from ice-cold to boiling.

349. The Human Ear. The organ of hearing consists of three parts—the outer, the middle and the inner ear. They are all shown in section in Fig. 358. The outer ear consists of that part *O* which is visible on the side of the head and which collects the sound, together with the tube *M* leading inwards from it. Closing this tube is the ear-drum *E* where begins the middle ear. This drum is a thin membrane extremely sensitive to changes in air pressure. The motion of the drum in and out is transmitted by three small bones (Fig. 359) which comprise a set of levers joined together. The drum gives its motion to one end of the hammer *H*; the other end moves the anvil *A* and this moves the stirrup *S* which then exerts a force, multiplied 30-fold by the mechanical advantage of the system of levers, upon the oval window *w* of the inner ear. This inner ear is filled with fluid through which the motion is transmitted to the brain, giving the person the sensation of sound.

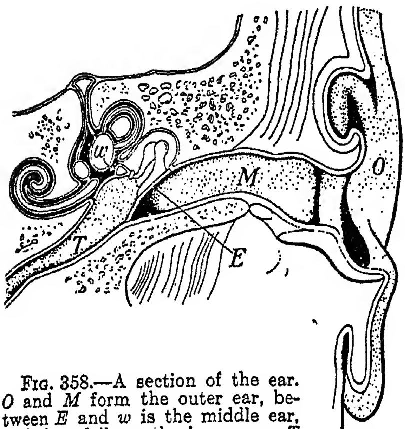


FIG. 358.—A section of the ear. *O* and *M* form the outer ear, between *E* and *w* is the middle ear, and then follows the inner ear. *T* is a tube, called the Eustachian tube, which leads to the back of the mouth.

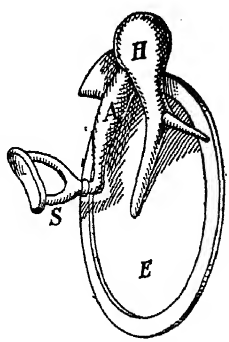


FIG. 359.—Showing on larger scale the ear-drum and the three articulated bones, the anvil a

The ear-drum is the model which has been copied in all instruments for producing and recording sounds, such as the telephone transmitter and receiver and the phonograph.

350. Stringed Instruments. In the piano there is a separate string, or a set of strings, for each note. The strings are of steel wire of different diameters, and for the bass notes they are overwound with other wire, being in this way made more massive without losing their flexibility. When a key is depressed, a combination of levers causes a soft hammer to strike the string at a point about $\frac{1}{7}$ of the length of the string from the end. If the instrument gets out of tune, it is repaired by re-adjusting the tensions of the strings.

The guitar has six strings of different diameters, the three lower-pitched ones being of silk overwound with fine wire. The strings are tuned to E_1, A_1, D, G, B, E', where D is the note next above middle C and has 293·6 vibrations per second. There are little strips across the finger-board called "frets", and when the player presses the strings down by the fingers against them, the strings are shortened and give out the other notes (Fig. 360).

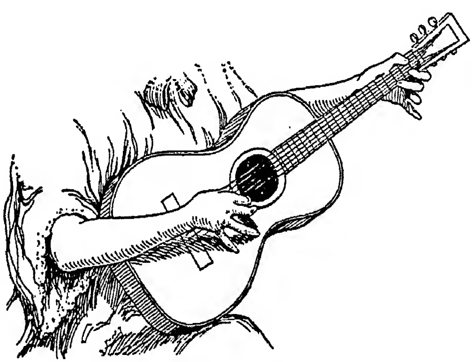


FIG. 360.—The guitar. With the left hand the strings are shortened by pressing them against the 'frets,' while the note is obtained by plucking with the right hand.

In the familiar ukelele there are four strings, tuned to G, C, E, A, with frequencies proportional to 18, 12, 15, 20. There are twelve frets, and the other notes are obtained by pressing the strings against them (Fig. 361).

There are four strings on the violin, tuned to G_1, D, A, E', where D is next above middle C of the piano. The frequencies are proportional to 18, 27, 40, 60. The other notes are obtained by shortening the strings by means of the fingers, but as there are no frets to guide the performer, he must judge the correct positions of the fingers himself.

The mandolin is of the "lute" family and is of great antiquity. Its strings are arranged in four pairs of unisons tuned like the violin. It is twanged by means of a plectrum or pick.

Exercise. The A string of the violin has a frequency of 435 vibrations per second. Compute that of each of the others.

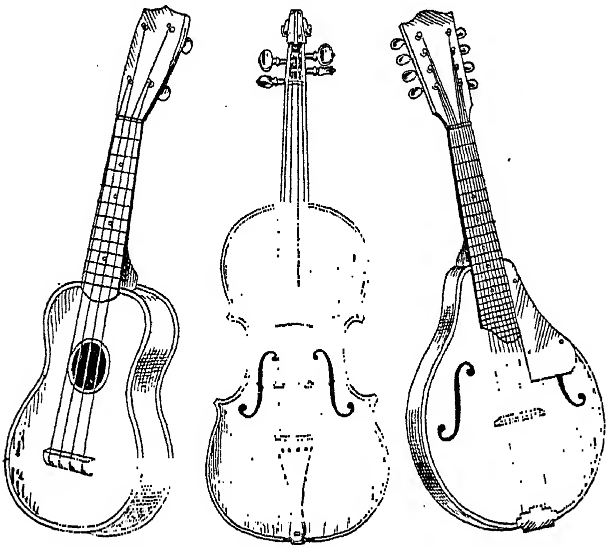


Fig. 361—Ukelele, violin, mandolin.

(*Left*) The ukelele is of Portuguese origin, but has been developed and popularized by the Hawaiians. (*Middle*) The violin pictured above was made by the famous Stradivari in 1703. Modern violins are of the same shape. (*Right*) A modern mandolin (Neapolitan). The backs of some older mandolins are shaped like an egg-shell.

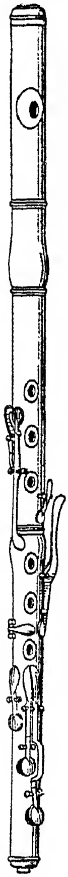
351. Organ: Pipes and Reeds. The action of organ pipes has been explained in § § 337, 338. In large organs they vary in length from 2 or 3 inches to about 20 feet, and some of them are conical in shape.

The flageolet or "tin whistle" (Fig. 362) acts like an organ pipe. The part used in producing a note is that from the lip to the nearest open hole,

Fig. 362.—A flageolet or "tin whistle".

When all the holes are closed the length used is *ac* and the wave-length of the sound emitted is twice *ac*; when all are open, the length is *ab* and the note much higher.

and by closing the holes with the fingers the player lengthens the part used and obtains lower notes. The flute (Fig. 363) is somewhat similar in principle. A current of air is blown



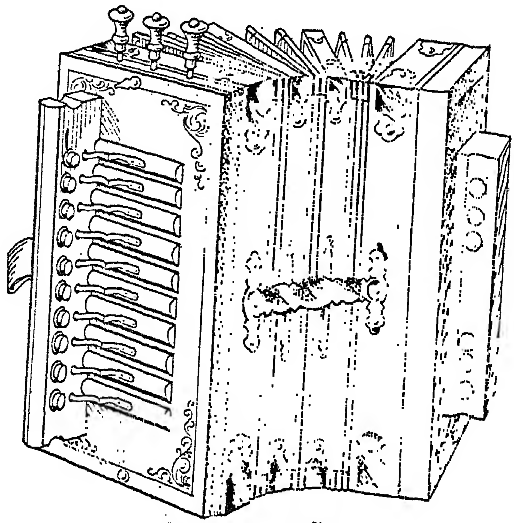
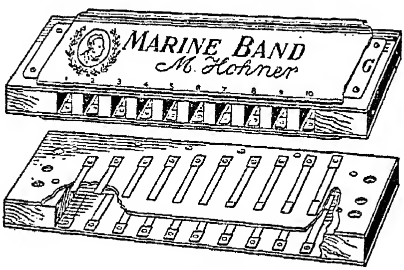


Fig. 364.—Accordion.
One of the smallest members of the organ family; invented by Damian of Vienna in 1829.



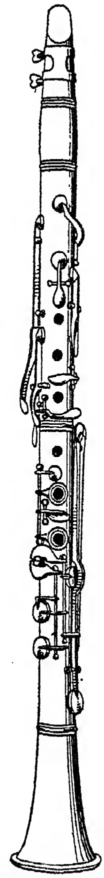


Fig. 363.—The flute.

Fig. 365.—Mouth-organ or harmonica.
Above, the instrument complete. *Below*, with portions removed to show the reeds.

Fig. 367.—The clarinet.

across the opening which is near one end and the air column within is set in vibration.

In the ordinary household organ, the mouth-organ (Fig. 365), the accordion (Fig. 364), and some other instruments the vibrating body is a reed, such as is shown in

Fig. 366. The tongue *A* vibrates in and out of an opening which it accurately fits, the motion being kept up by the current of air which is directed through the opening.

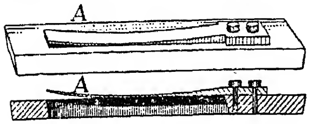


FIG. 366.—An organ reed. The tongue *A* moves in and out of the opening. This is called a *free* reed.

In some organ pipes there are reeds, but the note produced is due chiefly to the air column in the pipe, the reed simply serving to set it in vibration.

A clarinet is shown in Fig. 367. It has holes in the tube which are covered by keys or by the fingers. The air in the tube is put in vibration by means of a reed made of cane (*R* in Fig. 368). The reed is very flexible, and the note heard is that of the air column not of the reed, which simply covers and uncovers the opening in the mouthpiece, being too large to pass into the opening. It is called a **striking** reed, that in Fig. 366 being a **free** reed. The saxophone and oboe are similar to the clarinet.

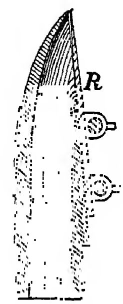


FIG. 368.—Mouthpiece of the clarinet. The reed *R* covers the opening.

352. Vibrations Produced by Player's Lips. The bugle, cornet and other such instruments consist essentially of an open conical tube, the larger end terminating in a bell while at the smaller end is a cup with a rounded edge against which the tense lips of the player are steadily pressed. The lips thus constitute a reed, and by their vibrations waves are set up in the air within the tube. In this way the fundamental and the various harmonics of the air column in the tube are pro-

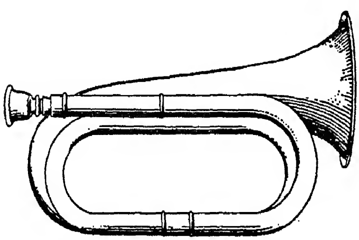


FIG. 369.—The bugle.

The bugle is illustrated in Fig. 369. The length of tube is fixed, and the notes producible are the fundamental and about 5 overtones. Its compass is rather narrow.

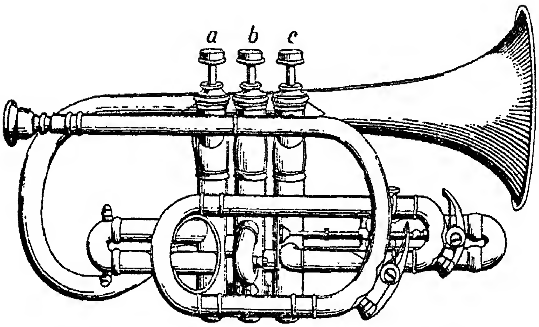


FIG. 370.—By the valves a, b, c, the air column is divided into different lengths.

In the cornet, by means of three valves a, b, c (Fig. 370), the air column may be divided into different lengths, and a series of overtones is obtained with each length.

In the trombone, on the other hand, besides obtaining overtones by suitable blowing, the pitch is varied by altering the

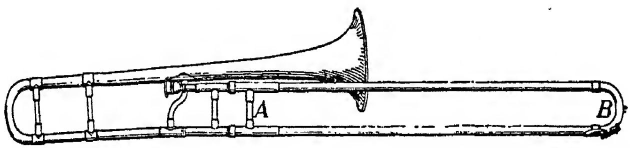


FIG. 371.—A slide trombone.

length of the tube. This is done by means of a U-shaped portion, AB (Fig. 371), which can slide with gentle friction upon the body of the instrument.

353. Vibrations of Bars. In Fig. 372 is a series of suitably constructed bars which when struck with a small mallet give the musical scale. The bars are supported at their nodes and there is a loop at the centre and at each end. The pitch of the note given depends on the length and the thickness of the bar and, of course, on the material used. In some cases the material is wood and the instrument is called a xylophone, which in Greek means "wood-sound." But strips

of glass or metal may be employed and they may rest on strings or on narrow pieces of wood covered with felt.

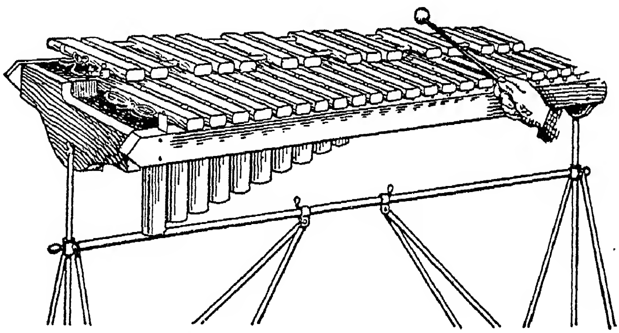


FIG. 372.—A modern xylophone.
Note the resonators beneath. It is played with two light hammers.

Such instruments as these have been constructed by native peoples. In Fig. 373 is shown one which has, beneath the bars, resonators made from hollowed-out gourds. In such a case it is generally called a marimba and a clever performer

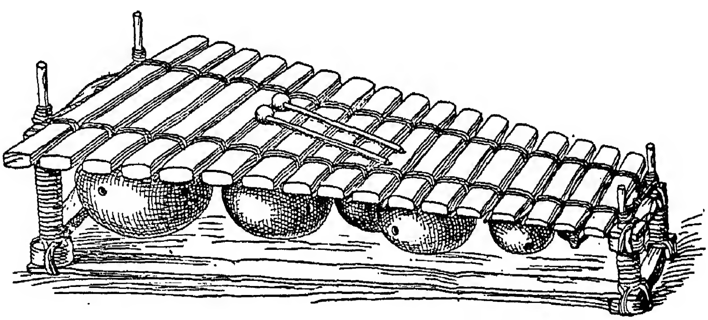


FIG. 373.—A native marimba (Congo).
(Drawn from the instrument in the Royal Ontario Museum, Toronto).

sometimes gets surprising music from it. Some dinner gongs made with strips of metal, usually of the same length but of different thicknesses, placed over resonators, when struck with a soft hammer give a fine volume of harmonious tones.

354. The Automobile Horn. The automobile horn is hardly a musical instrument, but it provides a good example of a sound produced by a vibrating plate. In the common type there is a small electric motor, the armature *A* (Fig. 374) of which carries at one end a toothed wheel *B*. When the button is pressed, the armature rotates very rapidly, and the teeth of the wheel strike on a little knob *C* at the middle of a diaphragm *D*. The vibrations of this diaphragm produce the sound, and the conical tube *E* projects it outward. The pitch of the sound at first is low, but the armature quickly gets up speed and the pitch is raised.

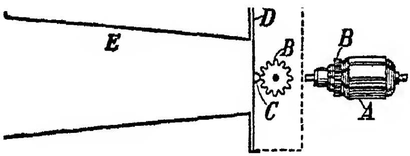


FIG. 374.—Explaining the action of an automobile horn. Armature seen separate.

In the telephone receiver a thin iron diaphragm is set in vibration by variations in the strength of a magnet. It is explained in § 586. In the radio loud-speaker the action is somewhat similar.

355. The Phonograph. This instrument was invented by Edison in 1877. Its construction is extremely simple, and one is astonished that such wonderful results can be obtained so easily.

At first the records were on tin-foil wrapped about a cylinder; after that a cylinder of wax was used; and now the records are on hard thin discs 10 to 12 inches in diameter. Upon the disc there is a long spiral groove, beginning at the edge and ending near the centre. In one type of record this groove varies in depth, that is, it is alternately deeper and shallower or it is a succession of "hill and dale." In the other type the groove is of uniform depth but its course is from side to side.

For the former kind the sound-box or reproducer is constructed as in Fig. 375. A small diamond with a sharp point is mounted at the end A of the short arm of a lever, while the end B of the long arm is attached by a flexible cord C to the diaphragm D, which is across the mouth of a diverging cone F, called the tone arm. The diaphragm is of vegetable fibre and is re-inforced by a layer of cork E. As the diamond point runs along the groove it moves up and

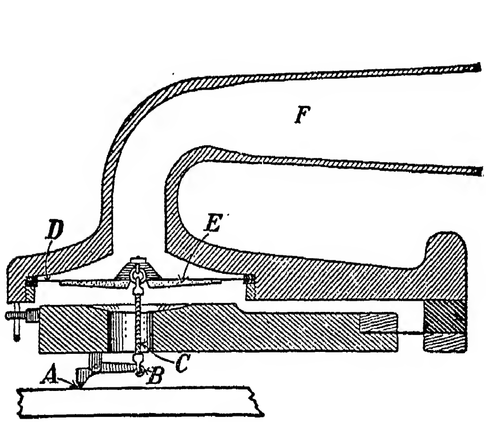


FIG. 375.—Section of the Edison reproducer, for records of the 'hill-and-dale' type.

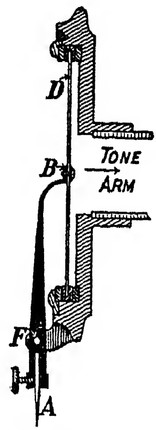


FIG. 376. — Section of reproducer for lateral or side-to-side records.

down, and this motion, somewhat magnified, is transmitted to the diaphragm. The motions of the diaphragm set up waves in the air, which pass along the tone-arm, then into the horn and then into the surrounding space.

For the other style of record the reproducer is such as shown in Fig. 376. Here a needle A is in the short arm of a lever, the end B of the long arm being connected to the diaphragm D. As the end of the needle runs along the groove it moves from side to side, this motion sets up motions in the diaphragm and the sound thus produced passes along the tone arm and out as before.

PART VII—LIGHT

CHAPTER LIII

LIGHT, ITS NATURE AND ITS MOTION IN STRAIGHT LINES

356. Light Radiation. When in the study of physics we speak of *light*, we mean the external agency which, if allowed to act upon the eye, produces the sensation of "seeing" or of "brightness." Most objects do not give out light of themselves. If you were to take them into a perfectly darkened room, you would not see them. But when light from some outside source, such as the sun, falls on them, they reflect it to our eyes and we see them. Some objects, however, such as a glowing coal or a lighted lamp, can be seen without the aid of any external source of light. Such are said to be self-luminous.

Some bodies, such as glass, mica, water, etc., allow light to pass freely through them and are said to be **transparent.** **Opaque** substances entirely obstruct the passage of light; while **translucent** bodies, such as ground glass, oiled paper, etc., scatter the light which falls upon them, but a portion is allowed to pass through.

For the transmission of sound, the air or some other material medium is necessary (§ 286), but such is not the case with light. Exhausting the air from a glass vessel does not hinder the passage of light through it, but rather facilitates it. Again, we receive light from the sun, the stars and other heavenly bodies, and as there is no matter out in those great celestial spaces, the light must come to us through a perfect vacuum. Indeed, it travels millions of millions of

miles without giving up any appreciable portion of its energy to the space it comes through.

We do not understand the process by which we obtain the sensation, but we believe that to produce it work must be done. It seems that the source of light—the sun, a candle, an electric light—radiates energy, which, upon reaching the eye, changes its form and produces the sensation of brightness.

357. Light Travels in Straight Lines. It is a common observation that light travels in straight lines. We assume the truth of this in many everyday operations. The carpenter could not judge that an edge was straight or the marksman point his rifle properly were it not so. When light is admitted into a darkened room—through a knot-hole in a barn, for instance—we can trace the straight course of the light by the dust particles in the air. The path along which the light travels is called a **ray**. The rays themselves cannot be seen, but when they fall upon the particles of matter, these are illuminated and reflect light to the eye.

358. Pin-hole Camera. An interesting application of the fact that light moves in straight lines is in the pin-hole camera. Let MN (Fig. 377) be a box having no back end and a hole in the front end. In front of it place a candle or other bright object, AB, and over the front hole stretch tin-foil. In this prick a hole C with a pin, and over the back of the box stretch a thin sheet of paper.

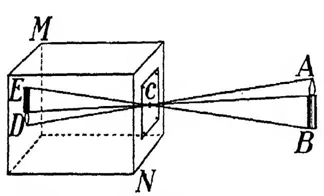


FIG. 377.—Pin-hole camera. C is a small hole in the front. An inverted image of the candle is seen on the back of the box.

The light from the various portions of AB passes through the hole C and forms on the paper an image DE, of the candle. This can be seen best by throwing over the head and the box a dark cloth. (Why?) The image is inverted, since the light travels in straight lines, and the rays cross at C.

If now we remove the paper, and for it substitute a photographic plate, a "negative" may be obtained just as with an ordinary camera; indeed the perspective of the scene photographed will be truer than with most cameras. The chief objection to the use of the pin-hole camera is that with it the exposure required, compared to that with the ordinary camera, is very long; but excellent pictures of out-of-door scenes can be taken with a camera which almost any one can make.

It is evident that to secure a sharp, clear image, the hole C must be small. Suppose that it is made twice as large. Then we may consider each half of this hole as forming an image, and as these images will not exactly coincide, indistinctness will result. On the other hand, the hole must not be too small. As it is reduced in size, other phenomena, known as diffraction effects, are obtained which cannot be discussed here.

359. Theory of Shadows. Since the rays of light are straight, the space behind an opaque object will be screened from the light and will be *in the shadow*. If the source of the light is small, the shadows will be sharply defined, but if it is of some size, the edges will be indistinct.

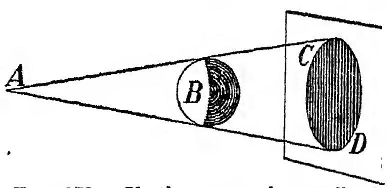


FIG. 378.—If the source be small, the shadow will be sharp. A is the source, B the object, CD the shadow.

Let A (Fig. 378) be a small source—an arc lamp, for instance—and let B be an opaque ball. It will cast on the screen a circular shadow CD with sharply defined edges. If now a sheet of ground glass is held in front of the arc lamp the source is made larger and the edges of the shadow are blurred.

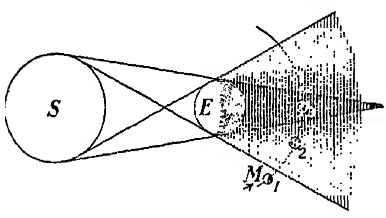


FIG. 379.—S is a large bright source, and E an opaque object. The dark portion is the *shadow*, the lighter portion the *penumbra*.

Next suppose the source is a body of considerable size, such as the sphere S (Fig. 379); it is evident that the only portion of space which

receives no light at all is the cone behind the opaque sphere *E*. This is called the **umbra,** or simply the **shadow,** while the portion beyond it which receives a part of the light from *S* is the **penumbra.** Let *M* be a body revolving about *E* in the direction indicated. In the first position it is entirely exposed to the light, in the second it is within the penumbra, and in the third position it is within the umbra or shadow.

If *S* represents the sun, *E* the earth, and *M* the moon, the figure will illustrate an eclipse of the moon. For an eclipse of the sun, the moon must come between the earth

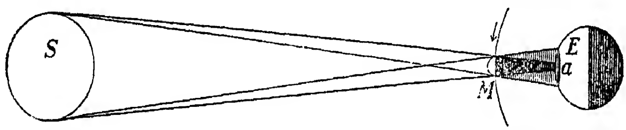


FIG. 380.—Showing how an eclipse of the sun is produced. A person at *a* cannot see the sun.

and the sun, as shown in Fig. 380. Only a small portion of the earth is in the shadow, and in order to see the sun totally eclipsed an observer must be at *a* on the narrow "track of totality." Figures 379 and 380 are not drawn to scale.

360. How is Light Transmitted? Scientists have been able to suggest only two methods by which energy can be transmitted from one place to another. A rifle bullet or a cannon ball has great energy, which it gives up on striking its target; in this case the energy is transferred by the forward bodily motion of a material body. Secondly, energy can be handed on without transference of matter, namely by wave-motion. (See § 289.)

The first method, which is commonly called the emission, or corpuscular, theory, was upheld by Sir Isaac Newton (1642-1727) and by others following him. According to it luminous bodies send out small particles, which produce the sensation of light when they strike the eye. This theory was commonly accepted for over a century and was finally discarded because there are some experimental results contrary

to it, and others which it cannot explain. If, then, we must discard it, we necessarily turn to the second method, which has been called the wave theory. For more than a century it was generally accepted by scientific men but in recent years some doubts regarding it have arisen. New reasons have been found for believing that light and some other radiation is sent out from its source in small units each of which is called a *quantum* (plural, *quanta*), very much as in the emission theory. To explain some phenomena we have to use the wave theory; for others the quantum theory is employed.

361. Ether. Now there cannot be waves without having a medium for them to travel in, and as the light-bearing medium is not ordinary matter, we are led to assume the existence of another medium which we call the **ether.** Light in the ether.

This ether must fill the great interstellar spaces of the universe; it must also pervade the space between the molecules and the atoms of matter, since light passes freely through the various forms of matter—solids, liquids and gases. We cannot detect it by any of our ordinary senses, we cannot see, feel, hear, taste, smell or weigh it, but as we cannot conceive of any other explanation of many phenomena, we are driven to believe in its existence, although some deny it.

362. Associated Radiations. It may be well to state here that the radiations which affect the eye never travel alone. Indeed those same radiations can also produce a heating effect and can excite chemical action—in the photographic plate, for instance. But associated with the light radiation are others which do not affect the eye at all. They assist healthy growth and destroy obnoxious germs, give us warmth necessary for life, produce chemical effects as revealed in the colours of nature, or give us communication by wireless telegraphy and radio.

These and many other effects are due to undulations of the ether, the chief difference among them being in the lengths of the waves. The light waves are all extremely short. The waves which produce the sensation of red are about $\frac{1}{30000}$ in. or $\frac{1}{1200}$ mm. in length, while those which produce the blue sensation are only half as long and radio waves are hundreds of metres in length.

We can *see* the waves moving on the surface of water or along a cord; we can *feel* the air, and with some effort, perhaps, can comprehend its motions; but to form a notion of how the ether is constructed and how it vibrates is a matter of excessive difficulty and indeed largely of pure conjecture. A very useful picture to have in one's mind is to think of the eye as joined to a source of light by numerous cords, and to consider the source as setting up in these cords transverse vibrations, which travel to the eye and give the sensation of light.

363. Waves and Rays. We consider light to be a form of energy which is transferred from place to place by means of *waves*. What then is the relation of waves to *rays?*

Let the light spread out in all directions from a source A (Fig. 381). The waves will be concentric spheres S_1, S_2, S_3 . . . , but the light will pass along the radii R_1, R_2, R_3 . . . , of these spheres. The rays thus are the paths along which the waves travel, and it is seen that the ray is perpendicular to the wave-surface.

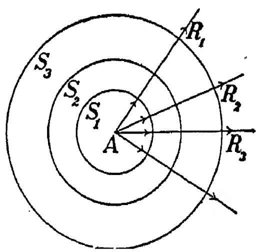


FIG. 381.—The wave spheres with A as c[entre]; the rays are radii of spheres.

If we consider a number of rays moving out from A (Fig. 382), we have what is known as a divergent pencil a, and the waves are concentric spheres continually growing larger. If the rays are coming together to a point, we have a convergent pencil

b, and the waves are concentric spheres continually growing smaller. If now the rays are parallel, as in c, we have a parallel beam, and the waves are plane surfaces, perpendicular to the rays. Such rays are obtained if the source is at a

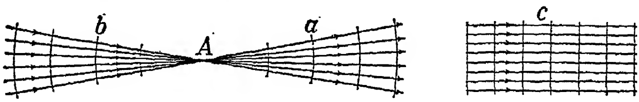


FIG. 382.—A convergent pencil, b; a divergent pencil, a; a parallel beam, c.

very great distance, so great that a portion of the sphere described with the source as centre might be considered a plane.

These results are easily illustrated experimentally by using an arc lamp and a lens. The lamp designed to accompany the optical disc shown in Fig. 395 (§ 375) is very convenient, the paths of the light being exhibited by chalk dust in the air.

QUESTION

What becomes of the waves of a convergent pencil (b, Fig. 382) after they come to a point?

364. Velocity of Light. The first clear evidence that light travels with a finite velocity was obtained by Roemer a young Danish astronomer. He made his discovery while observing the motions of the

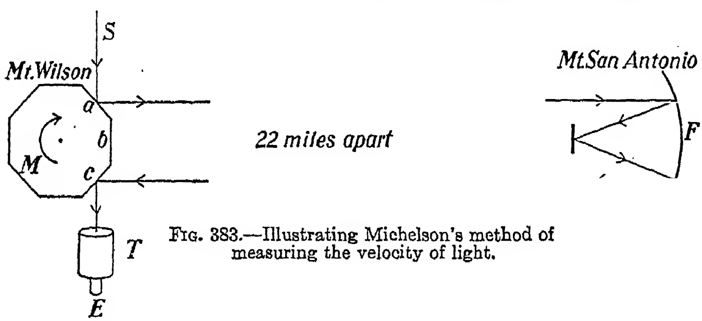


FIG. 383.—Illustrating Michelson's method of measuring the velocity of light.

moons of the planet Jupiter at the Paris Observatory in 1675. But beginning in 1850 the velocity has been measured directly on the earth's surface by several experimenters. It is enormously large and great skill is required to determine it.

The most accurate measurements were made in 1926 at Mount Wilson in California by Michelson of Chicago. The principle of the method

he used may be explained with the aid of Fig. 383, but the actual apparatus employed was complicated and very difficult to handle. Light proceeds from a bright source S (an arc lamp), strikes the face a of an 8-sided mirror M from which it is reflected as shown by the arrow to the distant concave mirror F. From this it is reflected to the small plane mirror m, thence to F again and thence back to the face c of the mirror M and thence into the telescope T and into the eye placed at E. The rotating mirror and other parts of the apparatus were set up on Mount Wilson and the concave mirror was mounted on Mount San Antonio, 22 miles distant.

First, let us suppose the mirror M is at rest and the apparatus is perfectly adjusted. The eye at E will see the source S after the light has travelled along the path indicated from Mount Wilson to Mount San Antonio and back, a total distance of 44 miles. Next, let the mirror be rotated about an axis perpendicular to the plane of the paper in the direction shown by the bent arrow. It is clear that when the light which strikes the face a and goes along the path shown arrives back at the mirror M, the face c will not be in the position shown in the figure but will have moved from it, so that the light will not go down the telescope and the eye will not receive it. But the mirror M may be speeded up faster and faster until it rotates so fast that during the time that the light goes from a over to the mirror F and back again the face b will have moved into the present position of face c. Under these circumstances the light will enter the telescope and the eye will see the source S again. To do this the mirror must turn one-eighth of a rotation while the light travels the double path to the distant station and back.

The task of the experimenter was to make all the very delicate adjustments at the two stations, then rotate the mirror fast enough and then keep it rotating uniformly until all the observations could be made. The mirrors were made, some of glass, some of steel, and they had 8, 12 or 16 faces. One with 8 faces is shown in its mounting in Fig. 383a. The rate of rotation varied from 264 to 528 per second. The final result for the velocity of light in a vacuum—which is the velocity in the great spaces of the universe—was 299,796 km. or 186,284 mi. per second. The velocity in air is about 40 miles less than the above. For ordinary purposes we may take the velocity of light to be 186,000 mi. or 300,000 km. per second.

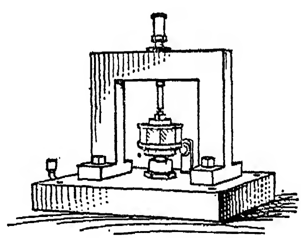


FIG. 383a.—One of the mirrors used in measuring the velocity of light.

QUESTIONS AND PROBLEMS

1. A photograph is made by means of a pin-hole camera, which is 8 inches long, of a house 100 feet away and 30 feet high. Find the height of the image?

2. A pin-hole camera box is 8 inches long, and the image of a tree 200 feet away is $2\frac{1}{2}$ inches high. Find the height of the tree.

3. Using an ordinary oil-lamp, obtain the shadow cast upon the wall by a vertical rod, (*a*) with the flame turned edgewise, (*b*) with the flat face turned to the rod. What difference do you observe? Account for it.

4. Why is the shadow obtained with a naked arc lamp sharp and well-defined? What difference will there be when a ground-glass globe is placed around the arc?

5. On holding a hair in sunlight close to a white screen the shadow of the hair is seen on the screen, but if the hair is a few inches away, scarcely any trace of the shadow can be observed. Explain this.

6. The shadow on the ground of a telephone pole in bright sunlight is not sharply defined. Explain why.

7. If the mirror (in Fig. 383) is rotating 528 times per sec. and it makes one-eighth of a rotation while the light travels 44 miles what is the velocity of light?

8. Taking the velocity of light to be 186,000 miles per second and the circumference of the earth to be 25,000 miles, how many times about the earth could light travel in one second?

9. The distance from the earth to the sun is 93,000,000 miles. Find the time required to travel this distance (*a*) by a railway train going 60 miles an hour; (*b*) by sound travelling with a speed of 1120 ft. per sec.; (*c*) by light whose speed is 186,000 miles per sec.

10. Light requires 8·6 years to come from Sirius, the brightest of the fixed stars, and 272 years to come from the Pole Star. Find the distance (in miles) of these two stars from us. (1 year = $365\frac{1}{4}$ days).

REFERENCES FOR FURTHER INFORMATION

S. P. Thompson, *Light Visible and Invisible*, Lecture 1.
Edser, *Light for Students*, Chapters 1, 11, 13.
Preston, *Theory of Light*, Chapters 1, 2, 3, 19.
W. H. Bragg, *The Universe of Light*.

CHAPTER LIV

ILLUMINATION

365. Illumination. If you are reading a book by artificial light and cannot see the print properly, you naturally move closer to the source of light and thus increase the illumination of the page. You can, of course, produce the same effect by increasing the power or strength of the source, for instance, by turning on another lamp or lighting additional candles. The illumination of a
of light per unit area (i.e., per square inch or square cm.) which it receives.

It is evident, then, that illumination depends on two things, (1) the power of the source of light, and (2) the distance from the source.

366. Decrease of Illumination with Distance from Source. Consider a small square of cardboard BC held one foot from a small source of light A (Fig. 384), and one foot behind this place a white screen DE, a sheet of white paper, for instance. The shadow cast by BC on DE is a square, each side of which is twice that of BC, and hence its area is four times that of BC. Next, hold the screen at FG, one foot further away, or three feet from A. The shadow of BC will now have its linear dimensions three times those of BC and its area nine times that of BC; and so on. The area of the shadow varies as the square of the distance from the source A.

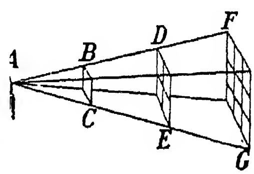


FIG. 384.—Area of DE is 4 times, and area of FG is 9 times that of BC.

Suppose now we mark off on the white screen an area 1 inch square and hold it at BC. The light which falls upon

this area will produce a certain illumination. Next, hold the screen at *DE*. The same amount of light which fell upon 1 square inch at *BC* will now be spread over an area of 4 square inches, and hence the illumination will be $\frac{1}{4}$ as great as before. Again let it be held at *FG*. The same amount of light will now be spread over 9 square inches, and the illumination will be $\frac{1}{9}$ that at the first position; and so on.

Thus we obtain the following important law:

The illumination varies inversely as the square of the distance from the source of light.

This law is so important that it will be well to illustrate it further.

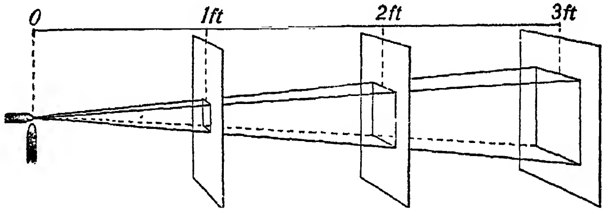


Fig. 385.—Experimental demonstration of the law of inverse squares.

Experiment. Remove the condenser from a projecting lantern (preferably one with an arc lamp) and at the distance of 1 ft. put a plate with a small square hole in it 1 inch to the edge (Fig. 385). Through this the light will stream. Place a screen immediately behind the plate and then successively at distances 2 ft., 3 ft., etc., *from the light source,* measure the side of the bright square projected on the screen at each of these distances, and calculate the areas of each of these squares. It will be found that they are approximately in the proportion of 1, 4, 9, etc., that is 1^2, 2^2, 3^2, etc. But the amount of light falling on each of these areas is the same in each case.

Thus we see that

The illumination at 2 ft. $= (\frac{1}{2})^2$ that at 1 ft.

The illumination at 3 ft. $= (\frac{1}{3})^2$ that at 1 ft.

The illumination at 4 ft. $= (\frac{1}{4})^2$ that at 1 ft.

and so on, or the inverse square law as before.

This is the fundamental law upon which all methods of comparing the powers of different sources of light are based.

It should be carefully observed that for this law to hold, the source of light must be small and must radiate freely in all directions. The headlight of a locomotive or an automobile, for instance, projects the light mostly in one direction, and the decrease in illumination will not vary according to the above law.

Again, it is evident that the illumination is directly proportional to the power of the source sending out the light, so that finally we conclude **Illumination** $= \dfrac{\text{Power}}{(\text{Distance})^2}$

367. Measuring the Power of a Source. To state definitely the illuminating power of any source of light we should express it in terms of some fixed standard unit. We have definite standard units for measuring length, mass, time, heat, and most other quantities met with in physics; but no perfectly satisfactory standard of light has yet been devised.

The one most commonly used is the **candle.** The British standard candle is made of spermaceti, weighs 6 to the pound avoirdupois, and burns 120 grains per hour. The strength varies, however, with the state of the atmosphere and with the details of the manufacture of the wick. Yet notwithstanding this inconstancy, it is usual to express the illuminating power of a source in terms of the candle. Thus an incandescent electric lamp may be of 40 candle-power, or an arc lamp of 1000 candle-power.

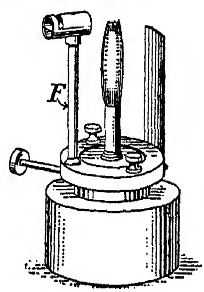


FIG. 386.—The Hefner standard lamp. The attachment F is for accurately adjusting the height of the flame.

A standard much used in scientific work is the Hefner lamp (Fig. 386). This is a small metal spirit-lamp with a cylindrical bowl 7 cm. in diameter and 4 cm. high. The wick-holder is a German-silver tube 8 mm. in interior diameter, 0·15 mm. thick, and 25 mm. high. The wick is carefully made to just fit the tube, and the height of the flame is adjusted to be 4 cm. The liquid burned is pure amyl acetate. The lamp is very constant, and its power is 98 per cent. of the British candle.

In ordinary commercial work incandescent lamps specially made and tested are used as standard light sources in measuring other sources of light.

368. Measurement of Illumination. In estimating illumination the unit commonly used is the **foot-candle**, which is the illumination given by a candle at the distance of one foot. If a candle is 5 feet from a surface the illumination of the surface is $\frac{1}{25}$ foot-candle, if 10 feet away it is $\frac{1}{100}$ foot-candle, and so on. If a lamp of 50 candle-power is 5 feet away, the illumination is $50 \times \frac{1}{25} = 2$ foot-candles.

In general, if L is the candle-power of the light-source and d is its distance in feet

$$\text{Illumination} = \frac{L}{d^2} \text{ foot-candles (see formula in § 366).}$$

The illumination supplied varies widely with the purpose for which it is required, and in recent years the demand for higher illumination has continually risen. We ask for illumination fifty times as great as our grandfathers were able to have.

At present the illumination in foot-candles for various services is about as follows:

	Good	Minimum
For stairways, passages, auditoriums	3	2
For reading room, library, office	12	8
For machine shop, ordinary machines	15	10
For engraving, sewing dark goods	50–100	25
For street lighting	$\frac{1}{4}$	$\frac{1}{20}$

The light of the full moon is about $\frac{1}{200}$ foot-candle.

If the walls of a room are light-coloured, the illumination due to a lamp in the middle of the room may be three or four times as great as it would be with black walls.

369. Foot-candle Meter. There are several types of instruments designed to measure directly the illumination at any place. That illustrated in Fig. 387 consists of two parts: a "photronic" cell which is affected when light falls on it,

and a micro-ammeter which measures weak electric currents. Both of these are referred to later in this book § 639.

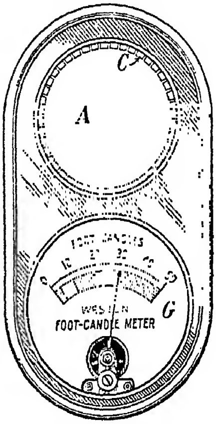


FIG. 387.—An instrument for measuring illumination.

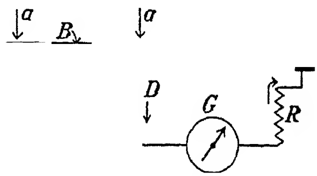


FIG. 388.—Diagram to explain the action of the instrument in Fig. 387.

The appearance of the instrument is shown in Fig. 387 and the principle of its operation in Fig. 388. In this diagram A is a circular metal plate (iron in this case) which is covered with a thin transparent layer B of a material (selenium in this case) which is sensitive to light. A small metal ring C is in contact with the film. This ring is joined through a resistance R to one terminal of the micro-ammeter G; the plate A is connected to the other terminal by the wire D.

When light falls on the film B as indicated by the arrows a, a, a, a very small current of electricity flows through G and the pointer moves over the dial. The strength of the current is approximately proportional to the intensity of the light and the dial is graduated to read directly foot-candles of illumination. By exposing the instrument anywhere the illumination there is given.

QUESTIONS AND PROBLEMS

1. Write two sentences using in each the terms *illuminating power* and *illumination*.

2. A sheet of paper is held 1, 2, 3, 10 ft. from a candle. What is the illumination of the paper at each distance?

3. A candle is 4 inches from a paper; what is the illumination of the paper?

4. A lamp with an illuminating power of 16 candles is placed 4 ft. from a book. What is the illumination of the book? If placed 2 ft. away what is the illumination?

5. Three lamps, each of 20 c.p., are 4 ft. above a table. Find the illumination of the table.

6. A 40-watt electric lamp at a distance of 4 ft. from a screen gives an illumination of 2 foot-candles. Find its c.p. and deduce how many watts it consumes per c.p.

7. The interior of many buildings is illuminated by indirect lighting. How is this accomplished and what are the advantages of this method?

8. A person is reading a book 7 feet from a 30 c.p. lamp and then moves up to 4 feet from the lamp. Compare the foot-candles in each case.

9. Good illumination for a reading room is about 12 foot-candles. At what distance would an 108 c.p. lamp give this illumination?

10. Which provides the greater illumination, a 50 c.p. lamp at 6 feet or a 100 c.p. lamp at 9 feet? Where should the latter be placed to give the same illumination as the former?

11. At what distance from a 20 c.p. lamp will the illumination be equal to that of the full moon?

12. What is the candle-power of a lamp which gives an illumination of 5 foot-candles at a distance of 6 feet?

CHAPTER LV

PHOTOMETERS

370. Joly's Diffusion Photometer. If we wish to compare the strength or illuminating *power* of one source of light with that of another source we use a *photometer*. Of such instruments several forms have been devised. That suggested by Joly is simple and satisfactory.

Two pieces of paraffin wax, each about 1 inch square and $\frac{1}{4}$ inch thick are cut from the same block of paraffin, carefully made of the same thickness and then put together with tin-foil between them (Fig. 389). Suppose we wish to compare the illuminating powers of two lamps, L_1 and L_2, for instance, an electric lamp and a candle.

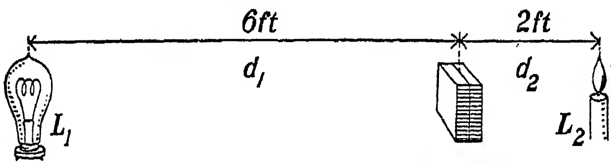


FIG. 389.—Comparing two lamps by the Joly photometer.

Move the photometer back and forth between the two lamps until the two blocks of paraffin are equally illuminated. Let its distance from L_1 be 6 feet and from L_2 be 2 feet.

If the candle were 1 foot from the photometer the illumination of the right-hand block would be 1 foot-candle, but as its distance is 2 feet the illumination is $\frac{1}{4}$ foot-candle.

Again, the lamp, of power L_1, is 6 feet from the photometer, $\frac{L_1}{6^2}$

$\frac{L_1}{36}$ foot-candles.

But the illumination of each block is the same.

Hence $$\frac{L_1}{36} = \tfrac{1}{4}, \text{ or } L_1 = 9 \text{ candles.}$$

In the general case let

L_1 = power of 1st lamp,
L_2 = power of 2nd lamp,
d_1 = distance of 1st lamp from photometer,
d_2 = distance of 2nd lamp from photometer.

$$\text{Then illumination of left block} = \frac{L_1}{d_1^2},$$

$$\text{and illumination of right block} = \frac{L_2}{d_2^2}.$$

But these illuminations are equal.

Hence $$\frac{L_1}{d_1^2} = \frac{L_2}{d_2^2}, \text{ or } L_1 = \qquad L_2.$$

In Fig. 389 $d_1 = 6$ ft., $d_2 = 2$ ft., and therefore $L_1 = 9L_2$

371. Verification of the Law of Inverse Squares. The Joly photometer may be used to verify the law of inverse squares (Fig. 390). Place 1 candle at one end of a board and 4 candles at the other. Now move the photometer until the two paraffin blocks are equally illuminated, and measure its distance from the 1 candle and from the 4 candles. The latter will be twice the former. Next, replace the 4 candles by 9 and adjust as before. The distance from the 9 candles will be 3 times that from 1.

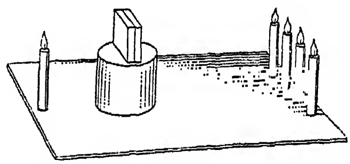


FIG. 390.—If the blocks are equally illuminated, the 4 candles are twice as far from the photometer as the single candle.

Thus if the distance is doubled, the illumination is reduced to $\frac{1}{4}$, since it requires 4 times as many candles to produce equality. In the same way, if the distance were n times as great, we should require n^2 candles to produce an illumination equal to that given by the single candle.

372. Grease-spot or Bunsen Photometer. The essential part of this photometer is a piece of unglazed paper with a grease-spot on it. Such a spot is more translucent than the ungreased paper, so that if the paper be held before a lamp, the grease-spot appears brighter than the other portion, while if held behind the lamp, it appears darker.*

Now move the grease-spot screen between the two light-sources L_1, L_2 (Fig. 391) to be compared until it is equally bright all over its surface. Then it is evident that what illumination the screen loses by the light from L_1 passing through, is precisely compensated by the light from L_2 transmitted through it. Thus the illumination due to each lamp is the same. Hence, if d_1, d_2 are the distances from the screen, of L_1, L_2, respectively,

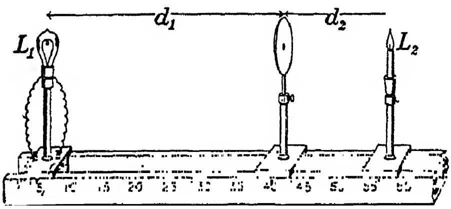


FIG. 391.—The Bunsen grease-spot photometer.

$$\frac{L_1}{} \qquad \frac{L_2}{d_2^2},$$

as before.

373. Shadow or Rumford Photometer. The method introduced by Rumford is to stand an opaque rod R (Fig. 392) vertically before a screen AB, and allow shadows from the two lamps to be cast on the screen.

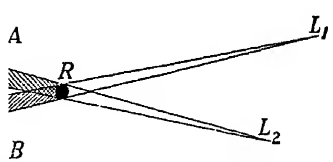


FIG. 392.—Rumford's shadow photometer. The lights L_1, L_2 are adjusted until the ... y a rod R on the screen are

If the screen is of ground-glass, it should be viewed from the side away from the

*Drop a little melted paraffin on the paper (thin drawing paper or filter paper), and after it has become hard, remove the excess of paraffin with a knife. Place the paper between two pieces of blotting-paper and run a moderately hot iron over it, thus making a grease-spot on the paper about 1 inch in diameter. Cut from the paper a circular disc 4 or 5 inches in diameter with the spot at its centre, and mount it on a suitable support.

lamps; if of opaque white paper (white blotting paper is best), the observer should be on the same side as the lamps.

It is evident that the portion *ab* is illuminated only by the lamp L_1, and the portion *cd* only by the lamp L_2.

Now move the lamps until the portions *ab*, *cd* are equally bright (or equally dark), and then measure the distance of L_1, from *b* and of L_2 from *c*. Let these distances be d_1, d_2, respectively.

Then, as before, $\dfrac{L_1}{d_1^2} = \dfrac{L_2}{d_2^2}$.

PROBLEMS

1. A candle is 2 ft. from a Joly photometer and when an electric lamp is 8 ft. on the other side the two paraffin blocks are equally illuminated. What is the candle power of the lamp?

2. A Joly photometer is placed midway between 2 candles. Then one candle is moved until it is 3 times as far from the photometer. How many similar candles must be put along with it so that the two paraffin blocks may be equally illuminated?

3. A lamp and a candle are placed 2 m. apart and a Joly photometer is in adjustment between them when 50 cm. from the candle. Find the c.p. of the lamp.

4. Find the c.p. of a lamp which at 40 cm. from a Bunsen screen gives equal illumination with a 25-c.p. lamp at 50 cm. on the other side.

5. A 20-c.p. lamp 10 cm. from a screen just balances an arc lamp 60 cm. away on the other side. Find the c.p. of the arc lamp.

6. Two standard candles near together are placed on one side of the screen of a Bunsen photometer and 20 inches from it. How far must a 16-c.p. electric lamp be placed on the other side to cause the grease-spot to disappear?

7. You wish to compare a candle and an oil-lamp flame by means of a shadow photometer. If the lamp is 12 times as powerful as the candle, and the latter is 15 in. from the screen, where will the lamp be placed when it just balances the candle?

8. In a Rumford photometer it is found that the shadows are of equal depth when one of the lights is at a distance of 110 cm. from the screen and the other at a distance of 200 cm. from it. Compare the illuminating powers of the lights.

9. When using a Rumford photometer (Fig. 392), the distance L_1c was found to be 50 inches and L_2b was 20 inches. Compare the illuminating powers of L_1 and L_2.

10. A candle and a gas-flame which is four times as strong are placed 6 feet apart. There are two positions on the line joining these two sources where a screen may be placed so that it may be equally illuminated by each source. Find these positions.

11. Distinguish between illumination and illuminating power. How does the illumination of your book depend on its distance from the source and the power of the source?

12. Describe and explain the appearance of a grease spot on white paper when viewed first by reflected light and then by transmitted light.

13. Explain clearly the function of the tin-foil in Joly's Diffusion Photometer.

14. How would you verify the law of inverse squares by using a lamp, a number of candles and a grease-spot photometer?

REFERENCES FOR FURTHER INFORMATION

EDSER, *Light for Students*, Chapter 1.

CHAPTER LVI

REFLECTION OF LIGHT: PLANE MIRRORS

374. The Laws of Reflection. A mirror is a highly polished surface used to reflect light. Generally it is made of glass with a layer of silver on the rear surface, but the silver may be on the front surface or there may be no silver at all. The behaviour of light when it falls upon a plane mirror is well illustrated in the following way.

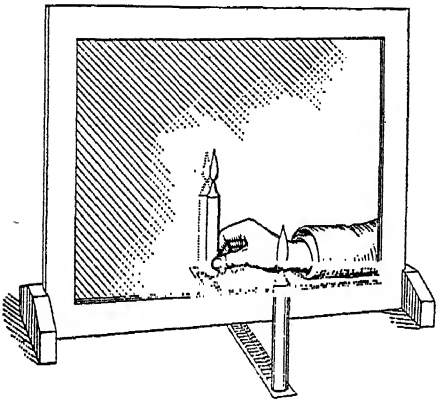


FIG. 393.—A lighted candle stands in front of a sheet of plate glass. Its image is seen by the experimenter, who, with a second lighted candle in his hand, is reaching round behind and trying to place it so as to coincide in position with the image of the first candle.

Experiment. Place a lighted candle in front of a sheet of thin (unsilvered) plate glass, and let it stand on a paper (or other) scale arranged perpendicular to the glass (Fig. 393). We see an image of the candle on the other side. Now move a second candle behind the glass until it coincides in position with the image.

This can be done very accurately by employing the "method of parallax." Hold two fingers in a vertical position about six inches apart and in line with the eye and move the eye from side to side. The nearer finger appears to move to the right when the eye is moved to the left and to the left when the eye is moved to the right. Now bring the two fingers nearer together. The closer they are, the less is the relative movement. Similarly, when the image and the second candle coincide, there will be no motion of one relative to the other when the head is moved from side to side.

It will be found that the two candles are both on the paper scale and are at equal distances from the glass plate.

We thus learn that *if an object be placed before a plane mirror, its image is as far behind the mirror as the object is in front of it, and the line joining object and image is perpendicular to*

Thus light goes from the candle, strikes the mirror, from which it is reflected, and reaches the eye as though it came from a point as far behind the mirror as the candle is in front of it. Of course the image is not real, that is, the light does not actually go to it and come from it—it only appears to do so. But the deception is sometimes perfect and we take the image for a real object. This illusion is easily produced if the mirror is a good one and its edges are hidden.

From the above experimental result we may deduce a geometrical law. Let M N (Fig. 394) be a section of a plane mirror. Light proceeds from A, strikes the mirror and is reflected, a portion being received by the eye E. To this eye the light *appears* to come from B, where $AM = MB$ and AB is perpendicular to MN.

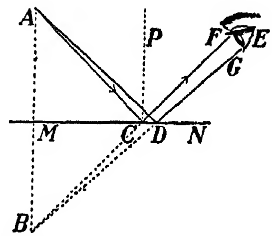


FIG. 394.—AC is an incident ray, CF the reflected ray, and CP the normal to the surface MN. Then angle of incidence ACP is equal to angle of reflection FCP.

Consider the ray AC, which, on reflection, goes in the direction CF.

In the triangles AMC, BMC, we have $AM = MB$, MC is common, and angle AMC = angle BMC, each being a right angle.

Hence the triangles are equal in every respect, and so the angle ACM = angle BCM.

But angle BCM = angle FCN, and hence the angles ACM and FCN are equal to each other.

From C let now CP be drawn perpendicular to MN. It is called the *normal* to the surface at C. At once we see angle ACP = angle FCP.

Now AC is defined to be the incident ray, CF the reflected ray, ACP the *angle of incidence* and FCP the *angle of reflection*.

Hence we can state the first law of reflection thus:

The angle of incidence is equal to the angle of reflection.

A second law should be added, namely:

The incident ray, the reflected ray and the normal to the surface are all in one plane.

375. The Optical Disc. This apparatus is very useful for demonstrating the fundamental laws of optics. On a stand *A* (Fig. 395) is mounted a circular disc *B* about 13 inches in diameter, which is graduated in degrees in both directions from a zero line. It is also provided with thumb-screws, by which mirrors, lenses and prisms can be attached to it near the centre. The curved metal shield *C* is pierced by a number of narrow horizontal slits through which "rays" of light can be projected. The disc and the shield can be rotated independently about the same horizontal axis through the centre of the disc and at right angles to it.

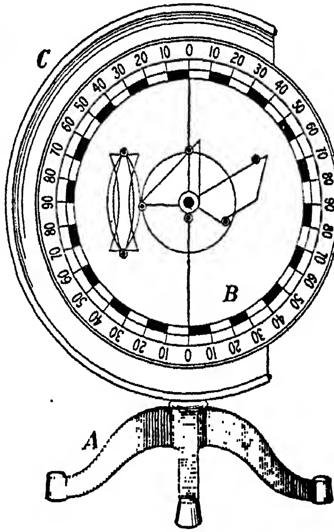


Fig. 395.—The optical disc, for demonstrating the laws of optics.

To verify the first law of reflection mount the plane mirror *D* (Fig. 396*a*) at the centre of the disc, with the face of the mirror at right angles to the zero line. Allow sunlight, or a parallel beam from a lantern or a focussing flashlight, to enter by one of the slits, the others being kept covered. By moving the disc one can make the ray strike the mirror at any angle from 0° to 90°, and since it lights up the disc in its passage to and from the mirror, the

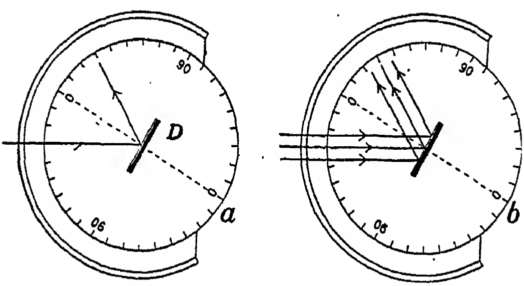


Fig. 396.- -Demonstrating that the angle of incidence is equal to the angle of reflection.

angles of incidence and reflection can be read directly from the circular scale. In the diagram these angles are each 30°.

If all the slits are opened the action of the mirror on a "beam" of light can be demonstrated (Fig. 396*b*).

The optical disc will be referred to later when curved mirrors, lenses and prisms are dealt with.

376. Regular and Irregular Reflection. When light falls on a mirror, it is reflected in a definite direction and the reflection is said to be **regular.** Reflection is also regular from the still surfaces of water, mercury and other liquids.

Now an unpolished surface, such as paper, although it may appear to the eye or the hand as quite smooth, will exhibit decided inequalities when examined under a microscope. The surface will appear somewhat as in Fig. 397, and consequently the normals at the various parts of the surface will not be parallel to one another, as they are in a well-polished surface. Hence the rays when reflected will take various directions and will be scattered.

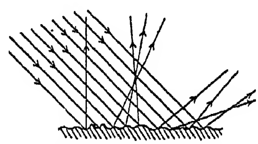


Fig. 397.—Scattering of light from a rough surface.

It is by means of this scattered light that objects are made visible to us. When sunlight is reflected by a mirror into your eyes, you do not see the mirror but the image of the sun formed by the mirror. Again, if a beam of sunlight in a dark room falls on a plate of polished silver, practically the entire beam is diverted in one definite direction, and no light is given to surrounding bodies. But if it falls on a piece of chalk, the light is diffused in all directions, and the chalk can be seen. Printing on glazed paper is often hard to read on account of regular reflection getting into the eyes, or the light not being well diffused. It is sometimes difficult to see the smooth surface of a pond surrounded by trees and overhung with clouds, as the eye considers only the

reflected images of these objects; but a faint breath of wind, slightly rippling the surface, reveals the water.

377. How the Eye Receives the Light. An object AB (Fig. 398) is placed before a plane mirror MM, and the eye of the observer is at E. The image $A'B'$ is easily drawn. The light which reaches the eye from A will appear to come from A', which is the image of A and which is as far behind MM as A is before it.

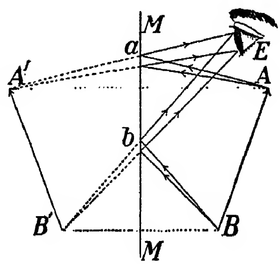


FIG. 398.—How an eye sees the image of an object before a plane mirror.

It is, therefore, by the pencil AaE that the point A is seen. In the same way the point B is seen by the small pencil BbE, and similarly for all other points of the object.

It will be observed that when the eye is placed where it is represented in the figure, the only portion of the mirror which is used is the small space between a and b.

Exercise. Draw a figure of a person standing before a vertical mirror and show that for him to see himself from head to foot the mirror need be only half his height. Draw a figure for the person at several distances from the mirror. At what place is the used portion of the mirror the least?

378. Lateral Inversion. The image in a plane mirror is not the exact counterpart of the object producing it. The right hand of the object becomes the left hand of the image. If a printed page is held before the mirror, the letters are erect but the sides are interchanged. This effect is known as **lateral inversion.** If a word is written on a sheet of paper and at once pressed on a sheet of

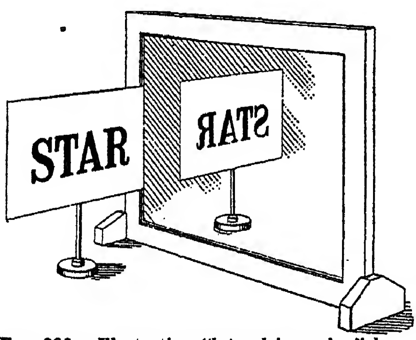


FIG. 399.—Illustrating "lateral inversion" by a plane mirror.

blotting-paper, the writing on the blotting-paper is inverted; but if it is held before a mirror, it is reinverted and becomes legible. The effect is illustrated in Fig. 399, showing the image in a plane mirror of the word STAR. It may be remarked, therefore, that on looking in a mirror we do not "see ourselves as others see us."

379. Reflections from Parallel Mirrors. Let us stand two mirrors on a table, parallel to each other, and set a lighted candle between them. An eye looking over the top of one mirror at the other will see a long vista of images stretching away behind the mirror. These are produced by successive reflections.

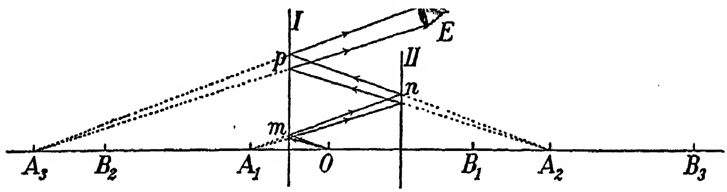


FIG. 400.—Showing many images produced by two mirrors *I*, *II*, parallel to each other.

In Fig. 400, *I* and *II* are the mirrors and *O* the candle. A_1 is the image of *O* in *I*, A_2 the image of A_1 in *II*, A_3 that of A_2 in *I*, and so on. Also B_1 is the image of *O* in *II*, B_2 that of B_1 in *I*, B_3 that of B_2 in *II*, and so on. The path of the light which produces in the eye the third image A_3 is also shown. It is reflected three times, namely, at *m*, *n* and *p*, and from the figure it will be seen that the actual path *OmnpE*, which the light travels, is equal to the distance A_3E from the image to the eye.

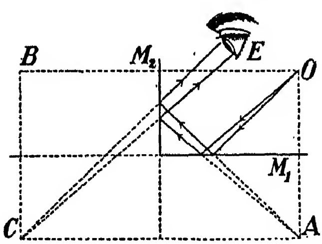


FIG. 401.—Images produced by two mirrors placed at right angles.

380. Images in Inclined Mirrors. Let the mirrors M_1, M_2 (Fig. 401) stand at right angles to each other and *O* be a

candle between. There will be three images, A being the first image in M_1, B the first image in M_2, while C is the image of A in M_2 or of B in M_1, these two coinciding. In the diagram is shown the path of the light by which the eye sees the image at C.

381. The Kaleidoscope. If the mirrors are inclined at 60°, the images will be formed at the places shown in Fig. 402. They are all located on the circumference of a circle having the intersection of the mirrors as its centre, and an inspection of the figure will show how to draw them.

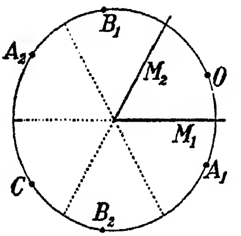


FIG. 402.—Images produced by mirrors inclined at an angle of 60°.

The kaleidoscope is a toy consisting of a tube having in it three mirrors forming an equilateral triangle, with bits of coloured glass between. The multiple images produce some very pleasing hexagonal figures. It was invented in 1816 by Sir David Brewster and created a great sensation.

QUESTIONS AND PROBLEMS

1. When sitting in your car at rest you see in your rearview mirror a car parked 20 ft. behind you and facing the opposite way. Where will the image in the mirror appear to be?

If the other car drives away at 30 mi. per hr. how will the image appear to move and how fast will it seem to go?

If when driving at the rate of 40 mi. per hr. you meet another car going at the rate of 50 mi. per hr. at what rate will the image of the other car appear to move? How far away will it appear to be in 20 sec.?

2. A mirror is tilted forward until 30° from the vertical, and a candle stands in front of it. Show by a diagram the position of the image, and also draw the rays by which an observer sees the top and the bottom of the candle. (See Fig. 398).

3. The sun is 30° above the horizon and you see its image in still water. Draw a diagram to show how the light reaches your eye, and find the angles of incidence and reflection.

4. Two mirrors are inclined at 45° and a candle is placed between them. By means of a figure show the position of the images. How many are there? How many when the angle is 60° and 90°? (See Figs. 401, 402.)

5. The following rule for finding the number of images seen in two inclined mirrors has been given: "Divide the angle between the mirrors into 360 and subtract 1." Test this in the case of angles 45°, 60° and 90° (Problem 4). Draw a figure and test it for 72°. Does it hold for 40°?

6. A ray of light is reflected successively from two mirrors placed at right angles to each other. Draw a figure to show its path, and show that after the second reflection it is parallel to its original direction.

7. Two mirrors are inclined at an angle of 60°. A ray of light travelling parallel to the first mirror strikes the second, from which it is reflected and, falling on the first, is reflected from it. Show that it is now moving parallel to the second mirror.

8. In using the heliograph (Fig. 403) for signalling, the plane mirror *A* is adjusted so that the light of the sun is reflected to the distant station. Dots and dashes are then made by operating the key *B*, which tips the mirror through a small angle and so throws the light alternately on and off the receiving station. If the sun is 40° above the horizon, at what angle with the horizon will the mirror have to be set in order that the reflected ray may be horizontal? If the mirror is tilted through 2° by working the key, through how many degrees will the reflected ray be deflected?

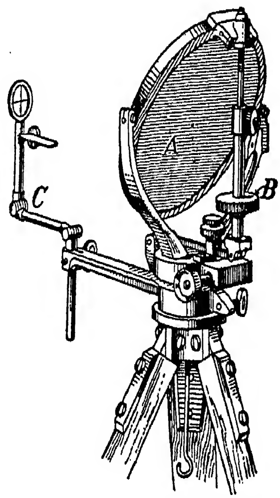


Fig. 403.—The heliograph used in the army. *A*, back of mirror.

9. On a moonlight night when the lake is covered with ripples, instead of an image of the moon being seen in the water, a long band of light is observed on its surface extending towards the moon. Explain this phenomenon by the aid of a diagram.

10. Show by a diagram how it is possible for a lady, by using two mirrors, to see an image of the back of her head.

REFERENCES FOR FURTHER INFORMATION

Nightingale, *Heat, Light and Sound*, Chapter 14.
Lewis Wright, *Light*, Chapter 2 (Good experiments).

CHAPTER LVII

REFLECTION FROM CURVED MIRRORS: CONCAVE

382. Curved Mirrors; Definitions. Curved mirrors are widely used—as reflectors behind oil-lamps, in automobile headlights, in searchlights, in reflecting telescopes, in flood-lighting, in instruments for examining the eye and the throat, and for many other purposes. Those used in optics are generally segments of spheres. If the reflection is from the outer surface of the sphere, the mirror is said to be **convex**; i inner surface, **concave**.

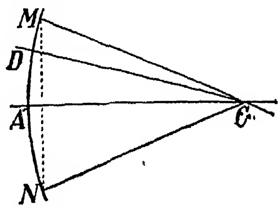


FIG. 404.—A section of a cal mirror.

In Fig. 404 MAN represents a section of a spherical mirror. C, the centre of the sphere from which the mirror is cut, is the **centre of curvature**, and CM, CA or CN is a **radius of curvature**; MN is the **linear aperture**, and MCN the -lar aperture; A, the middle point of the face of the mirror is the **vertex**; CA is the **principal axis**, and CD, any other straight line through C, is a **secondary axis.** Note also that all radii of a circle are at right angles to the circle, and hence CM, CD, CA and CN are normals to the mirror at the points M, D, A, N, respectively. We shall first consider a concave mirror.

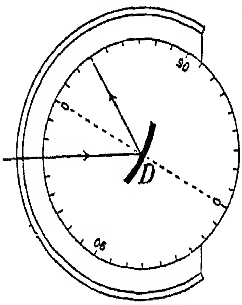


FIG. 405.—Finding the law of reflection at a concave mirror.

383. Action of a Concave Mirror. The laws of reflection hold for curved as well as for plane mirrors. The behaviour of rays of light when they fall on such mirrors can be well shown by means of the optical disc.

Experiment. Fit the concave mirror D (Fig. 405) to the disc so that the zero line of the disc coincides with the principal axis of the mirror and the vertex of the mirror is at the centre of the disc. Cause a ray, or a very narrow beam, of light to fall on the mirror at the vertex. Now, the principal axis is the normal to the mirror at the vertex and, consequently, the angles of incidence and reflection can be read directly from the scale on the disc. In Fig. 405 they are each 30°. Repeat with different angles of incidence and observe the angle of reflection in each case. It will be found that in every case the angle of reflection is equal to the angle of incidence.

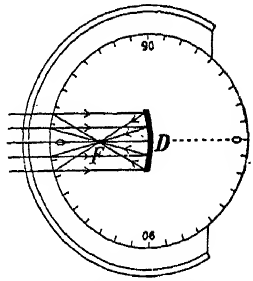


Fig. 406.—Parallel rays are verged to a point called the principal focus.

Next, let a number of rays* fall on the concave mirror parallel to the principal axis (Fig. 406). After reflection from the mirror they converge approximately to a point F, which is called the **principal focus of the mirror.**

384. How to Draw the Reflected Ray. Suppose QR (Fig. 407) to be a ray of light incident at R upon a concave mirror. We wish to draw the reflected ray. Join R to C the centre of curvature. Then RC is the normal to the mirror at R. By making CRS or r (the angle of reflection) equal to CRQ or i (the angle of incidence) we obtain RS, the reflected ray.

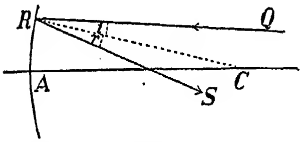


Fig. 407.—Reflection from a concave mirror.

385. Principal Focus. In Fig. 408 let QR be a ray parallel to the principal axis; then, making the angle CRS = angle CRQ, we have the reflected ray RS. But since QR is parallel to AC, angle CRQ = angle RCF. Hence angle FRC = angle FCR, and the sides FR, FC are equal.

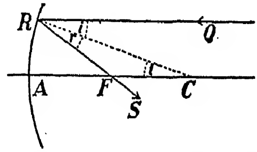


Fig. 408.—The ray QR, parallel to the principal axis AC, on reflection passes through the principal focus F.

Now if R is not far from the vertex A, FR and FA are nearly equal, and

*These rays may be obtained by projecting the light from a focussing flashlight through a comb.

hence AF is approximately equal to FC, that is, the reflected ray cuts the principal axis at a point approximately midway between A and C.

It is evident, then, that a beam of rays parallel to the principal axis, striking the mirror near the vertex, will be converged by the concave mirror to a point F, midway between A and C. This point is called the **principal focus**, and AF is the **focal length** of the mirror. Denoting AF by f and AC by r, we have $f = r/2$.

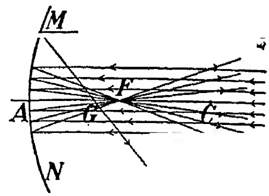


FIG. 409.—A beam of rays parallel to the principal axis passes, on reflection, through F, the principal focus.

In the case shown in Fig. 409 the rays actually pass through F, which is therefore called a **real focus**.

Rays which strike the mirror at some distance from A do not pass precisely through F. For instance, the ray QM after reflection cuts the axis at G; this *wandering* from F is called **aberration**, which amounts to FG for this ray.

386. Explanation by the Wave Theory. The behaviour of curved mirrors can be easily accounted for by means of the wave theory. In Fig. 410, $a\,b$, $a_1\,b_1$, $a_2\,b_2$, ... represent plane waves moving forward to the concave mirror. The waves reach the outer portions of the mirror first and are turned back, in this way being changed into spherical waves which contract, pass through F and then expand again.

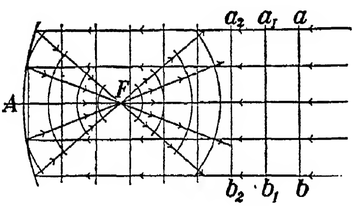


FIG. 410.—Showing how plane waves by reflection at a concave mirror are changed to spherical waves.

This action of a concave mirror is well illustrated in Fig. 411 from an instantaneous photograph of ripples on the surface of mercury. The plane (or straight-line) waves were produced by a piece of glass fastened to one prong of a tuning-fork. They move forward, as shown by the arrows, and meet a concave reflector, by which they are changed into circular waves converging to the principal focus. They pass through this and then expand again.

Exercise. (1) Draw a diagram like the photograph reproduced in Fig. 411, showing the paths of several "rays." What ultimately becomes of the waves on the surface of a liquid?

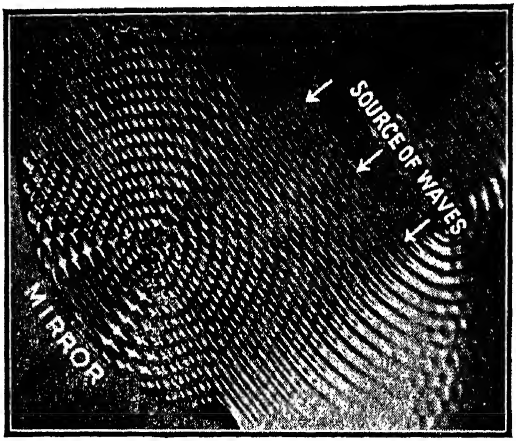


FIG. 411.—Photograph of waves on the surface of mercury.

387. Conjugate Foci. We have seen that light rays moving parallel to the principal axis are brought to a focus by a spherical mirror, but a focus can be obtained as well with light not in parallel rays. For instance, let the light diverge from P (Fig. 412); after reflection from the concave mirror it converges to P'.

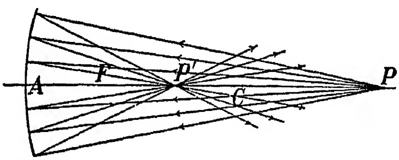


FIG. 412.—Conjugate foci in a concave mirror. P and P' are conjugate.

Now, it is evident that if the light originated at P', it would be converged by the mirror to P. Each point is the image of the other, and they are called **conjugate foci**.

In the case shown in Fig. 412, both foci are real, since the rays which come from one actually pass through the other. It is possible, however, for one of them to be **virtual**. Such a case is shown in Fig. 413. Here P' is conjugate

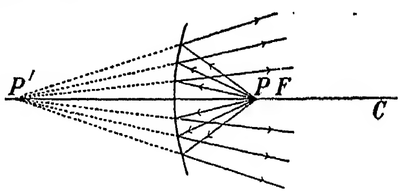


FIG. 413.—Conjugate foci in a concave reflector, one being virtual.

to P, but is virtual, that is, the light does not actually come from or go to P' but behaves as though it did. It will be noticed that P is between the mirror and F. In these circumstances the conjugate focus is virtual, in all others is it real.

Exercise. Draw the *waves* in these cases of conjugate foci, taking P at various positions on the axis.

388. Experiments with a Concave Mirror. (1) Into a darkened room take a concave mirror, and at the other end of the room place a lighted candle facing the mirror. The position of the image can be found by catching it on a small screen. It will be very near the principal focus, and will be real, inverted and very small. This enables us to determine the focal length of the mirror. If the sun is shining, hold the mirror in the sunlight and receive the image on a piece of paper. If sunlight is not available, find the position of the image of a distant object. Even a window at the opposite side of the room will give good results.

(2) Now carry the candle towards the mirror. The image moves out from the mirror and increases in size, but it remains real, inverted and smaller than the candle, until, when the candle reaches the centre of curvature, the image is there also and is of the same size. In this way we can determine the centre of curvature and, consequently, the focal length of the mirror.

(3) Next, bring the candle nearer the mirror; the image moves farther and farther away, and is real, inverted and enlarged. When the candle reaches a certain place near the principal focus, the image will be seen on the opposite wall, inverted, and much enlarged; but when the candle is at the focus, the light is reflected from the mirror in parallel rays—the image is at infinity.

(4) When the candle is at a point between the principal focus and the vertex, the reflected rays diverge from a virtual focus behind the mirror (see Fig. 413). No real image is formed, one cannot receive it on a screen, but on looking into the mirror one sees a virtual, erect and magnified image. Its position can be determined by the method of parallax explained in § 374. Use a hat-pin stuck in a rubber cork behind the mirror and seen above it as a 'finder.' Another hat-pin may be used as an object instead of the candle.

These results may be arranged in a table:

IMAGES WITH A CONCAVE MIRROR

Position of Object	Position of Image	Real or Virtual	Size	Erect or Inverted
Beyond c.c.	Betw. p.f. and c.c.	Real	Smaller	Inverted
At c.c.	At c.c.	Real	Same size	Inverted
Betw. c.c. and p.f.	Beyond c.c.	Real	Larger	Inverted
At p.f.	Rays parallel			
Inside p.f.	Behind mirror	Virtual	Larger	Erect

389. To Draw the Image produced by a Concave Mirror. Suppose PQ to be a small bright object placed before a concave mirror (Fig. 414). Now *all* the rays from the point Q after reflection pass through its image, and it is clear that we can locate the position of this image if we can draw any two rays which pass through it.

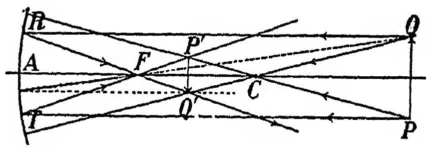


FIG. 414.—How to locate the image produced by a concave mirror.

Draw a ray QR, parallel to the principal axis; this will, upon reflection, pass through the principal focus F. Also, the ray QC will strike the mirror at right angles, and, when reflected, will return upon itself. The two reflected rays intersect at Q', which is therefore the image of Q. Draw the rays PT and PC; after reflection they meet in P' which is the image of P. It is evident then that $P'Q'$ is the image of PQ.

It is to be observed that the ray QF will, after reflection, return parallel to the axis AC, and will, of course, also pass through Q'.

By drawing any two of the three rays QR, QC, QF we can always find Q', the image of Q. It should be remembered,

that all the rays from Q, not just those drawn, will after reflection pass through Q'. Similarly with those from P and other points on PQ.

It will be very useful to draw the image of an object in several positions. In Fig. 415 the object PQ is between A and F. By drawing QR, parallel to the axis, and QT, which passes through the centre of curvature, we obtain Q', the image of Q; and by drawing similar rays from P we obtain P', and hence $P'Q'$ the image of PQ. It is virtual and behind the mirror.

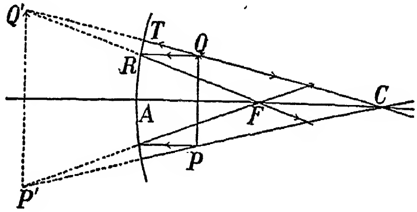


FIG. 415.—How to draw the image when the object is between the principal focus and the vertex.

Exercise. Draw the image when the object is between F and C.

390. Relative Sizes of Image and Object.

Let PQ be an object and $P'Q'$ its image in a concave mirror (Fig. 416). The ray QA which strikes the mirror at the vertex, is reflected along AQ', and the angle QAP = angle $Q'AP'$. Also, angle APQ = angle $AP'Q'$, each being a right angle, and hence the two triangles APQ, $AP'Q'$ are similar to each other.

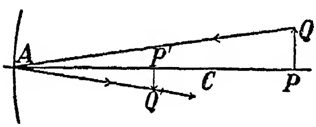


FIG. 416.—The size of the object PQ is to that of the image $P'Q'$ as their distances from the mirror.

The ratio of the length of the image to that of the object is called the **magnification.** Hence we have,

$$\text{Magnification} = \frac{P'Q'}{PQ} = \frac{AP'}{AP} \quad \frac{\text{distance of image from mirror}}{\text{distance of object from mirror}}$$

In the case illustrated in the figure the magnification is less than 1; in Fig. 415 it is greater than 1.

CHAPTER LVIII

REFLECTION FROM CURVED MIRRORS (CONCLUDED)

391. Action of a Convex Mirror. The behaviour of convex mirror may be exhibited by the optical disc.

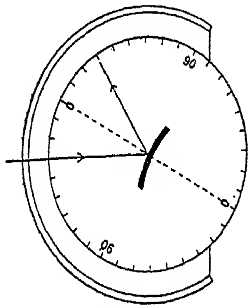


FIG. 417.—Reflection of a ray from a convex mirror.

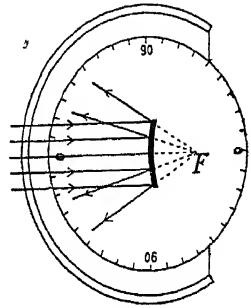


FIG. 418.—Reflection of parallel rays from a convex mirror.

Experiment. Attach the mirror to the disc so that its convex surface is at the centre of the disc and its principal axis is along the zero line of the disc (Fig. 417). Admit a ray and, as in Fig. 405, test with different angles of incidence. Again it will be found that the angle of reflection is always equal to the angle of incidence.

Then allow a number of parallel rays to fall on the mirror as in Fig. 418. After reflection they diverge as though they come from the point F behind. This point is the principal focus of the convex mirror.

392. To Draw the Ray Reflected by a Convex Mirror. In Fig. 419 the ray QR is incident at R upon a convex mirror. As in the case of a concave mirror, join R to C, the centre of curvature, and produce CR to T. Then TRQ is the angle of incidence; and making TRS equal to it we have RS, the reflected ray.

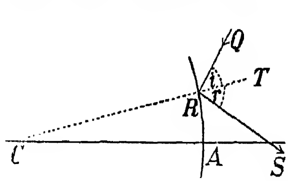


FIG. 419.—Reflection from a convex mirror.

393. Principal Focus of a Convex Mirror. For a convex mirror the same method is followed as for a concave mirror. In Fig. 420 a beam parallel to the principal axis is incident near the vertex. The reflected rays diverge in such a way that if produced backwards they pass through F, the principal focus. In this case the rays do not actually pass through F, but only appear to come from it, or it is a virtual focus. In the figure is also shown a ray QM, which strikes the mirror at some distance from the vertex. Upon reflection this appears to come from G, and FG is the aberration.

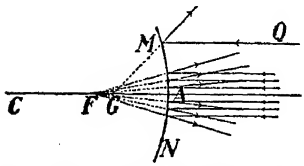


FIG. 420.—Showing reflection of a parallel beam from a convex mirror.

394. Experiment with a Convex Mirror. The method described in § 388 (4) may be used with a convex mirror.

If the candle is held before the mirror, the image is always virtual, erect and smaller than the candle. The method of parallax must be used to locate the image experimentally. The image of a distant object (a chimney answers well) is practically at the focus. This method of finding the focal length requires patience but it gives very satisfactory results.

A simple example of a convex mirror is the outer surface of the bowl of a silver spoon.

395. To Draw the Image in a Convex Mirror. The same method is used as in the case of a concave mirror (see Figs. 414, 415). In Fig. 421 the mirror is convex, and the image $P'Q'$ is virtual, erect, behind the mirror and smaller than PQ. It is always so in a convex mirror. Such a mirror is sometimes mounted on the fender of a truck or an automobile so that the driver may have a wide view of what is behind him.

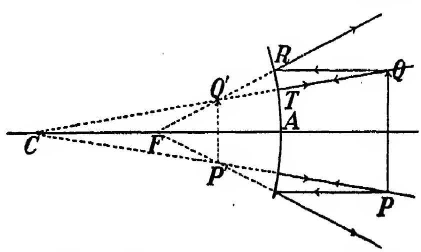


FIG. 421.—How to draw the image produced by a convex mirror.

396. The Rays by which an Eye sees the Image. In § 389 a graphical method is given for locating the image of an object, but the actual rays by which an eye sees the image are usually not at all those shown in the figures.

In Figs. 422, 423, 424 are shown actual rays from points P and Q which reach the eye. In each figure the image is supposed to have been obtained by the graphical method. The image is real and inverted in Fig. 422, virtual and erect in the other two cases.

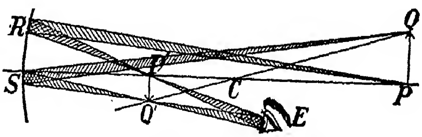


FIG. 422.—How the rays pass from the object to the eye. (Real image in concave mirror.)

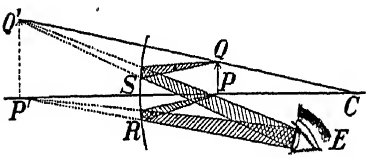


FIG. 423.—How the rays go from the object to the eye. (Virtual image in concave mirror.)

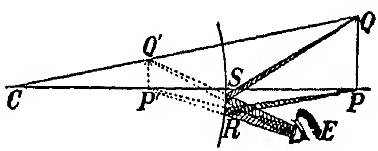
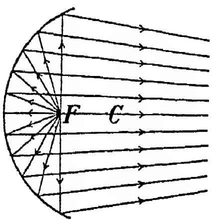


FIG. 424.—How the eye sees an object in a convex mirror. (Image always virtual.)

Now in each instance the light enters the eye as though it came from $P'Q'$. Join Q' to the outer edge of the pupil of the eye, forming thus a small cone with vertex at Q'. This cone meets the mirror at S, and it is clear that the light starts from Q, meets the mirror at S, is reflected there and then passes through Q' (really or virtually), and reaches the eye. In the figures are shown also rays starting out from P, the other end of the object. They meet the mirror at R, where they are reflected and then received by the eye. In the same way we can draw the rays which emanate from any point in the object.

It will be seen that for the eye in the position E, shown in the figures, the only part of the mirror which is used is that space from R to S. The rays which fall on other parts of the mirror pass above or below or to one side of the eye.

397. Parabolic Mirrors. In the case of a spherical mirror, only those rays parallel to the axis which are incident near the vertex pass very closely through the principal focus; if the angular aperture is large the outer rays after reflection pass through points some distance from the focus (see Fig. 409). Conversely, if a source of light is placed at the principal focus, the rays after reflection will not all be accurately parallel to the axis, but the outer ones (Fig. 425) will converge inward, and later on after coming together will spread out. Hence at a great distance the light will be scattered and weakened.



425.—Illustrating aviour of a spherical mirror of large angular aperture.

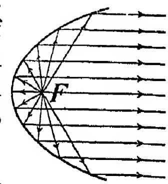


Fig. 426.—How a parabolic reflector sends out parallel rays.

Now a parabolic mirror overcomes this spreading of the rays. In Fig. 426 is shown a parabola. All rays which emanate from the focus, after reflection are parallel to the axis, no matter how great the aperture is. In Fig. 426a a parabola and a circle are compared. In a small portion near the vertex they almost coincide. Parabolic mirrors are used in searchlights and headlights. The source should be small, and if it is powerful, a beam can be sent out to great distances with little loss of intensity.

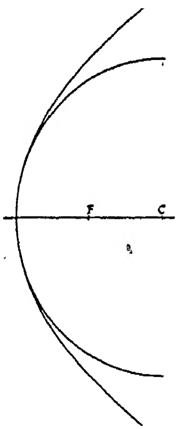


Fig. 426a.—A parabola and a circle of the same focal length.

Signalling Lamp. A late form of signalling lamp used in the British army is shown in Fig. 427. The filament C of the bulb B is placed at the principal focus of the concave parabolic mirror A which has a diameter of $3\frac{3}{4}$ inches. Signals sent by this lamp are readable in daylight with the naked eye at about 2 miles, and the total dispersion of the rays at that distance is only 160 yards. The bulb B is approximately 8 c.p. (4 watts).

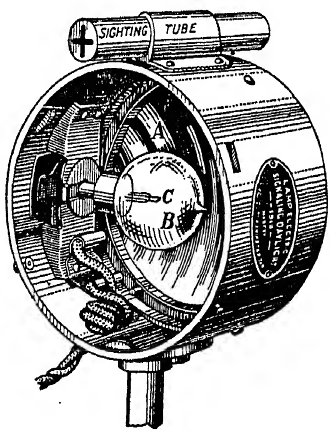


Fig. 427.—British army signalling lamp.

Divided Headlight. In navigating the Suez Canal at night the ship ordinarily has a parabolic headlight with an arc-light source so placed that a beam with a spread of about 12° is projected straight ahead. When another ship is approaching it is necessary to darken the central portion of the beam so that the eyes of the pilot of the approaching ship may not be dazzled by the bright light. In order to accomplish this the mirror is cut into halves which are then hinged together. The hinge is in the vertical and by rotating the two parts of the mirror about it (so that part a becomes a' and b becomes b' Fig. 428), the beam is split into two parts which illuminate the banks and the buoys but leave a dark central lane as shown in Fig. 429. The mirrors ordinarily employed in this service have a diameter of about 20 in. and a focal length of 10 in.

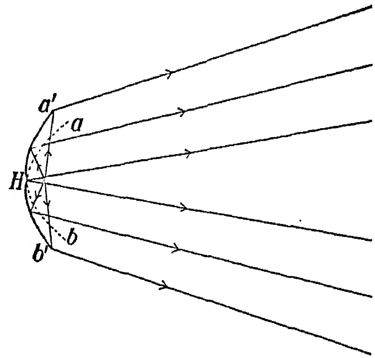


Fig. 428.—A parabolic mirror divided into two halves hinged at H.

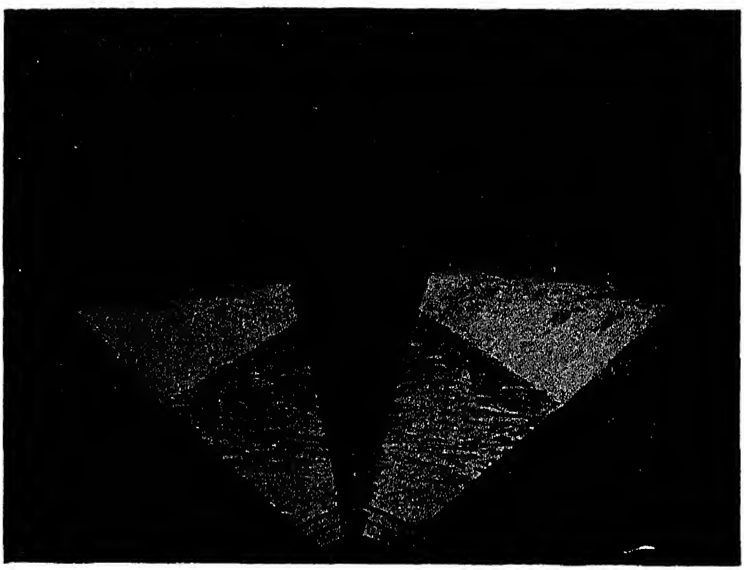


Fig. 429.—Illuminating the Suez Canal with a split mirror.

Automobile Headlight. Automobile headlights are now constructed with two separate filaments in the bulb. One is precisely in the focus of the reflector. When the current from the battery passes through it a beam of light is projected straight ahead. By pressing a button on the floor the current may be sent through the other filament which is made to be just above the focus. The beam from this filament is directed downwards and the glare in the eyes of a motorist coming in the opposite direction is greatly reduced.

Telescope Mirror. Another important use of the parabolic mirror is in the reflecting telescope. Such a mirror is made by grinding and polishing the upper surface of a glass disc to a parabolic form and then depositing on it a thin coating of silver or aluminium which provides a good reflecting surface. In Fig. 430 is a mirror 76 inches in diameter. A mirror 200 inches in diameter is being ground in California.

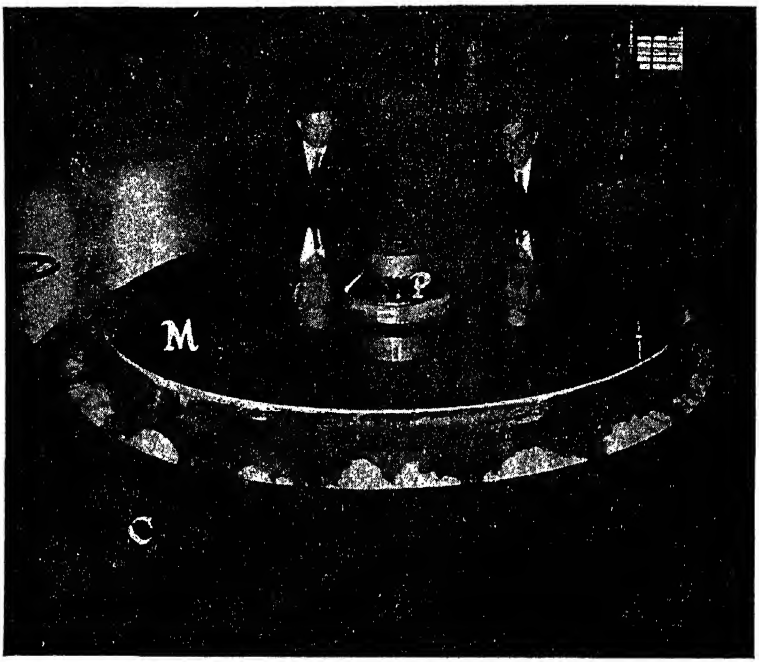


FIG. 430.—The great mirror of the 74-inch telescope of the David Dunlap Observatory. The glass disc is 76 in. in diameter, 11½ in. thick at the edge and 10½ in. at the centre. It is silvered on the upper surface. The mirror *M* is in its iron cell *C*. There is a hole through its centre and a plug *P* is seen in it. The distortion in the reflected images of the faces is due to the curvature of the surface.

QUESTIONS AND PROBLEMS

1. What is meant by (1) a real image and (2) a virtual image?

2. With what kind of mirror can an image be thrown upon the wall? Is it real or virtual, erect or inverted?

3. Draw diagrams to show how a concave mirror may produce (*a*) a real image smaller than the object and inverted; (*b*) a real image larger than the object and inverted; and (*c*) a virtual image larger than the object and erect.

4. In a shaving mirror the image is enlarged and erect. What sort of mirror is it? Where is its principal focus?

5. Give practical applications of concave and convex mirrors.

6. By geometry show that the focal length of a convex mirror is equal to half its radius of curvature (Fig. 421).

7. In a garden you sometimes see a silvered glass sphere on a pedestal. What sort of images will it show?

8. In an amusement resort there are two mirrors. One makes you appear very thin but of natural height; the other makes you appear very short but of unchanged width. What kind of mirrors are these?

9. Why is it desirable that in headlights the source of the light should be very small?

10. While you are looking into the headlight of a car get some person to press the control button on the floor. Observe that one filament is in the centre of the lamp and one above; and note how the beam is projected with each.

REFERENCE FOR FURTHER INFORMATION

Nightingale, *Heat, Light and Sound.*
Ingalls, *Amateur Telescope Making.*

CHAPTER LIX

REFRACTION

398. Effects due to Refraction. Many persons have noticed the odd appearance of a stick when held obliquely in the water; it seems broken at the surface of the water. A good time to observe this phenomenon is when you are rowing in the summer. Look along an oar; that part of it in the water will appear tilted up and not in line with the portion above the water.

Perhaps you have tried to spear a fish. If so, you have found that the fish was lower than it appeared to be. These peculiar results are due to **refraction,** which we may begin to study by the following experiments.

Experiments. 1. The apparatus in Fig. 431 is suitable for our purpose. The tank is about 15 x 15 x $2\frac{1}{2}$ inches. The front and ends are of glass, the rest of metal. White paper with a circular disc cut out of it is pasted on the front. The edge should be graduated, and vertical and horizontal diameters marked on the glass. Pour water into the tank until up to the horizontal diameter. If a little silver nitrate or fluorescin is added to the water and the space above it is filled with smoke the path of the light is made clearer. Now project a beam of light from a lantern or the sun and reflect it down to meet the surface of the water at the centre of the circle. If the beam is too thick, it may be made to pass through a narrow slit in a metal strip laid on top of the tank.

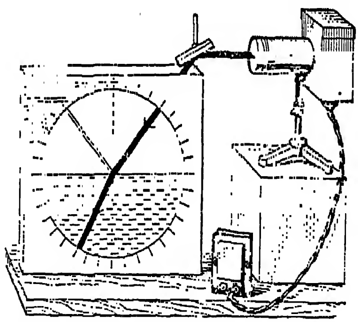


FIG. 431.—Arrangement to show refraction of light as it passes from air to water.

Observe now that while a part of the light is reflected from the surface of the water a large portion enters the water but abruptly changes its direction. If the light falls perpendicularly upon the surface, there will be no change of direction; but in all other cases there will be. **This**

change of direction when light passes from one medium to another is **called refraction.**

2. Next, let us use the optical disc. Fasten the semi-circular glass plate to the disc as shown in Fig. 432. Project a "ray" of light against the flat face of the plate. Some of the light will be reflected but a large portion will enter the glass and travel in a new direction. This is the refracted ray.

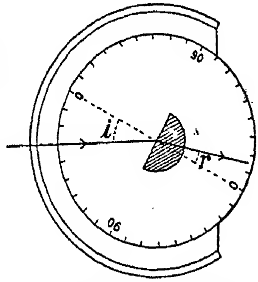


FIG. 432.—Refraction with the optical disc.

The angle between the incident ray and the normal (marked i) is the **angle of incidence,** and that between the refracted ray and the normal (marked r) is the **angle of refraction.**

Turn the disc so that the angle i may take the values 20°, 40°, 60°, and observe the corresponding values of r. They will be approximately 13°, 25°, 35°, respectively. As we shall see later, there is a definite relation between the corresponding values of i and r.

399. Further Experiments. The fact that light changes its direction of motion as it passes from one medium into another enables us to explain some simple experiments.

1. Place a coin PQ on the bottom of an opaque vessel (Fig. 433), and then move back until the coin is just hidden from the eye E by the side of the vessel. Let water be now poured into the vessel. The coin becomes visible again, appearing to be in the position $P'Q'$. The bottom of the vessel seems to have risen and the water looks shallower than it really is.

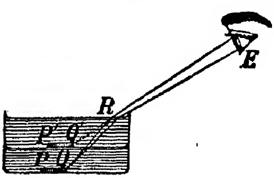


FIG. 433.—The bottom of the vessel appears raised up by refraction.

The reason for this is readily understood from the figure. Rays proceed from Q to R, and on leaving the water are bent away from the normal, ultimately entering the eye as though they came from Q'. Similarly rays from P will be refracted at the surface and will enter the eye as though they came from P'. As the light appears to come from P' and Q' the observer thinks the coin is there.

2. The familiar illustration of the bent stick, already mentioned, is explained in the same way

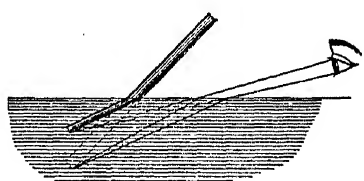


FIG. 434.—The stick appears broken at the surface of the water.

(Fig. 434). A pencil of light coming from any point on the stick, upon emergence from the water is refracted downwards and enters the eye as though it came from a point nearer the surface of the water. Thus the part of the stick immersed in the water appears lifted up.

400. Explanation of Refraction by Means of Waves. First, let us consider what might naturally happen when a battalion of soldiers passes from smooth ground to rough ploughed land. It is evident that the rate of marching over the rough land should be less than over the smooth. Let the rates be 3 and 4 miles an hour, respectively.

In the figure (Fig. 435) are shown the ranks of soldiers moving forward in the direction indicated by the arrows. The rank AB is just reaching the boundary between the smooth and the rough land, and the pace of the men at the end A is at once reduced. A short time later this rank reaches the position $a\ b$, part being on the rough and the rest still on the smooth ground. Next, it reaches the position $c\ d$, and then the whole rank reaches the position CD, entirely on the rough land. If now it proceeds in a direction at right angles to the rank, as shown by the arrows, it will move off in a direction quite different from that on the smooth ground. The succeeding ranks follow in the same manner, and the new direction of motion is AC.

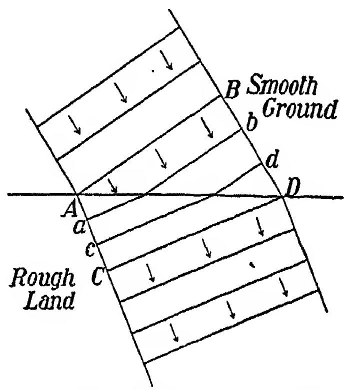


Fig. 435.—Illustrating how a change in direction of motion may be due to change in speed.

Now, it is clear that the space BD of smooth ground is marched over in the same time as the space AC of rough land, and as the rates are 4 miles and 3 miles an hour, respectively, we have

$$\frac{BD}{AC} = \frac{4}{3}.$$

We have used ranks of soldiers in the illustration but waves behave very similarly. In Fig. 436 is reproduced a photograph of waves on the surface of water. These waves were produced by attaching a piece of thin glass to one prong of a tuning-fork and then vibrating it just touching the surface. The waves move forward in the direction shown by the arrow, but on reaching the shallower water over a piece of glass lying on the bottom of the vessel, their speed is diminished and the wave-fronts swerve around, thus abruptly changing the direction of propagation. (Read again § 291.)

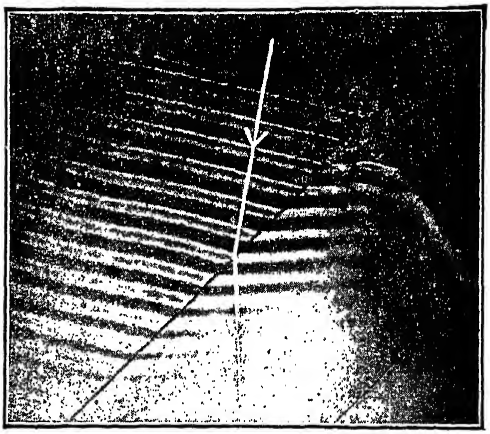


FIG. 436.—Plane waves on passing into shallower water are refracted as shown by the arrow. (Photograph by J. H. Vincent.)

401. Laws of Refraction. We have found in § 398 the angles of refraction corresponding to three angles of incidence when the light passes from air into crown glass. By further use of the optical disc the following table may be obtained. It gives the angles of refraction corresponding to nine angles of incidence ranging from 10° to 90°.

ANGLES OF INCIDENCE AND REFRACTION

$\angle i$	10°	20°	30°	40°	50°	60°	70°	80°
$\angle r$	7°	13°	20°	25°	30°	35°	38°	40°

Now let us draw a diagram for a pair of these angles, (say) 60°, 35° (Fig. 437). The rays of light fall on the glass at O and AON is the normal to the surface there. The incident ray is PO and the refracted ray is OQ. With O as centre draw a circle cutting these rays in P and Q, and from

these points draw PM, QN perpendicular to the normal AN, and measure their lengths. It will be found that

$$\frac{PM}{QN} \quad \frac{3}{2} \text{ (approximately).}$$

If we take any other pair of angles we shall find the ratio between the lengths of the perpendiculars to be the same. This ratio is called the **index of refraction** from air to crown glass. If we had used air and water (as in Fig. 431) the value of the index of refraction would have been

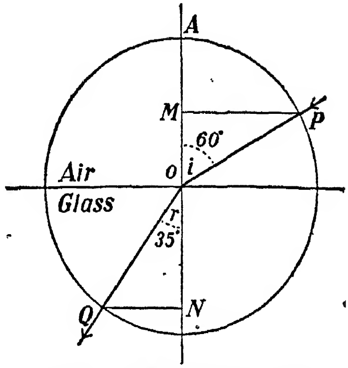


FIG. 437.—Angle of incidence and refraction.

Next, consider the angle in Fig. 438 between the two lines AB, AC. From C, any point in AC, draw CB perpendicular to AB. Then the ratio $\frac{CB}{CA}$ is defined to be the *sine* of the angle CAB.

FIG. 438.—CB/AC is the sine of CAB.

Coming back now to Fig. 437 we see that $\frac{PM}{OP}$ = sine of angle POM and $\frac{QN}{QO}$ = sine of angle QON.

Hence $\frac{\text{sine } POM}{\text{sine } QON} \quad \frac{PM}{OP} \quad \frac{QN}{QO} \quad \frac{PM}{QN}$. index of refraction,

or $$\frac{\text{sine of angle of incidence}}{\text{sine of angle of refraction}} \quad \text{index of refraction.}$$

We find, therefore, that **the sine of the angle of incidence divided by the sine of the angle of refraction is a constant quantity,** which is called the **index of refraction.**

This is the **first law of refraction.**

The second law of refraction is: The incident refracted ray and the normal to th plane.

Table of Indices of Refraction. The following table gives the values of the indices of refraction from air into various substances.

It must be remembered, however, that the indices are not the same for lights of all colours, those for blue light being somewhat greater than those for red. The values given here are for yellow light, such as is obtained on burning sodium (or common salt) in a Bunsen or a spirit flame.

INDICES OF REFRACTION (YELLOW LIGHT)

Crown-glass	1·51 to 1·56	Water	1·33
Flint-glass	1·61 to 1·79	Alcohol	1·36
Diamond	2·42 to 2·47	Olive-oil	1·48
Canada Balsam	1·53	Turpentine	1·47

It will be noticed that although alcohol, olive-oil and turpentine are lighter (that is, have smaller specific gravity) than water, they refract light more powerfully. They are said to be *optically denser* than water.

402. How to Draw the Refracted Ray. Suppose CO (Fig. 439) is a ray of light incident on the surface of water, at the point O. Draw the normal AO, and with O as centre describe a circle. Draw CM perpendicular to AO. Make OT three-quarters of CM, and from T draw a perpendicular to the surface, cutting the circle in c. Then Oc will be the refracted ray. If the lower medium were glass having an index of $\frac{3}{2}$, OT would be made two-thirds of CM.

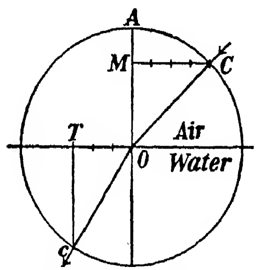


FIG. 439.—Method of drawing the refracted ray.

403. Relation between Velocity of Light and Index of Refraction. In Fig. 440 is shown the refraction of light-waves from air into water. The arrows show the direction in which the waves move before and after refraction. AB represents a wave just as it arrives at the surface of the water and CD shows it just when it is within the water. The angles i and r, of incidence and refraction, are marked and the values of the other angles are evident from the figure.

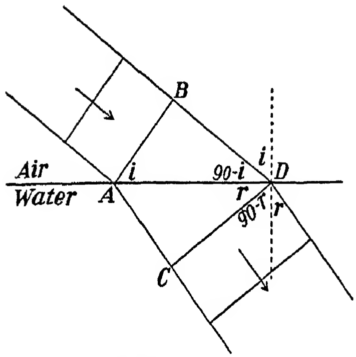


FIG. 440.—Showing passage of plane waves from air to water.

Now $\dfrac{\text{velocity in air}}{\text{velocity in water}} = \dfrac{BD}{AC}$ (as in § 400).

But $\dfrac{BD}{AD} = \text{sine } BAD = \text{sine } i$; and $\dfrac{AC}{AD} = \text{sine } CDA = \text{sine } r$.

Hence $\dfrac{\text{sine } i}{\text{sine } r} = \dfrac{BD}{AD} \div \dfrac{AC}{AD} = \dfrac{BD}{AC} = \dfrac{\text{velocity in air}}{\text{velocity in water}} =$ index of refraction.

As the index for water is 4/3, light travels in air 4/3 as fast as in water.

QUESTIONS AND PROBLEMS

1. In spearing fish one must strike lower than the apparent place of the fish. Draw a figure to explain why.

2. Explain the wavy appearance seen above hot bricks or rocks.

3. State the first law of refraction in words, and express it by a formula.

4. What is the relation between the index of refraction from one medium into another and the velocity of light in those mediums?

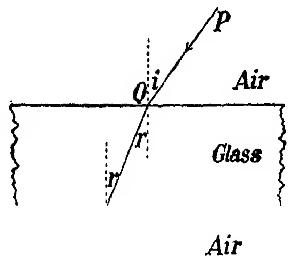
5. If the index of refraction from air into diamond is 2·47, find the velocity of light in diamond and the index from diamond to air. (Velocity of light in air = 186,000 mi. per sec.)

6. The index of refraction from air to water is 4/3, and from air to crown-glass is 3/2. If the velocity of light in air is 186,000 miles per second, find the velocity in water and in crown-glass; also the index of refraction from water to crown-glass.

CHAPTER LX

REFRACTION THROUGH PLATES AND PRISMS

404. Refraction Through a Plate. A plate is a portion of a medium bounded by two parallel planes. In Fig. 441, *PQRS* shows the course of a ray of light through a plate of glass. It is refracted on entering the plate and again on emerging from it. Since the normals at *Q* and *R* are parallel, the angles made with these by *QR* are equal. Each of them is marked *r*. Then, since the angles of incidence and refraction depend on the velocities of light in the mediums, and if we send the light along *SR*, it will pass through by the course *RQP*, it is evident that the angle between *SR* and the normal at *R* is equal to that between *PQ* and the normal at *Q*. Each of these is marked *i*.



It is clear, then, that the incident ray *PQ* is parallel to the emergent ray *RS*, and, therefore, that the direction of the ray is not changed by passing through the plate, though it is laterally displaced by an amount depending on the thickness of the plate. This can be easily illustrated by means of the optical disc.

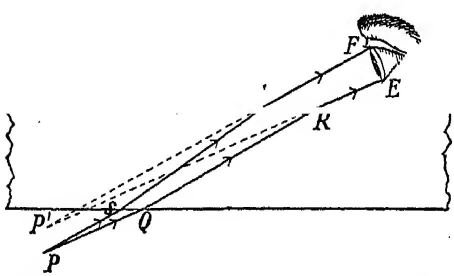


FIG. 442.—Showing why, when viewed through a glass plate, an object appears nearer.

405. Vision Through a Plate. Let *P* be an object placed behind a glass plate and seen by an eye *E* (Fig. 442). The pencil of light will be refracted as shown in the figure, *RE*, *TF* being

parallel to PQ, PS, respectively. The object appears to be at P', nearer to the eye than P is.

This effect is well illustrated by laying a thick plate of glass over a printed page. It makes the print seem nearer the eye, and the plate appears thinner than it really is.

406. Total Reflection. Up to the present we have dealt mainly with the refraction of light from a medium such as air into one which is optically denser, such as water or glass. When we consider the light passing in the reverse direction, we come upon a peculiar phenomenon.

Let light spread out from the point P, under water (Fig. 443). The ray PM, which falls perpendicularly upon the surface, emerges as MA, in the same line. Four rays are represented on either side of PM. They are marked a, b, c, d. The ray a is partially refracted out into the air, appearing as e, and partly reflected in the water as m. When the ray b reaches the surface a smaller proportion is refracted out as f and a larger proportion is reflected as n. When the ray c reaches the surface no part of it is refracted out, but the entire ray is reflected as g. All rays from P which strike the surface beyond B are totally reflected. The ray g is one of these. The incident ray is d and the reflected ray is h and these two rays are equally strong, except, of course for what is lost by absorption as the light passes through the water.

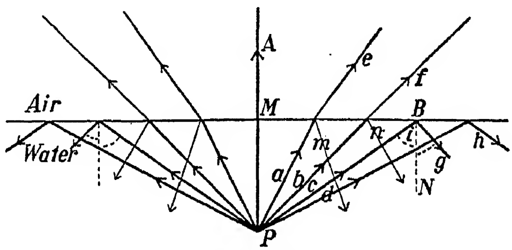


FIG. 443.—PB is the critical ray, and PBN (which is equal to BPm) is the critical angle for water and air.

The angle PBN (marked i) is just at the critical position where all the light begins to be internally reflected and is

angle for the two mediums water and air. The angle BPM is equal to PBN, as is evident from the diagram.

If a ray is travelling in any medium in such a direction that the emergent ray just grazes the surface of the medium, then the angle which the ray travelling in the (denser) medium makes with the normal is called the critical angle.

The values of the critical angles for some substances and air are approximately as follows:—

Water.......$48\frac{1}{2}°$	Crown-glass.....$40\frac{1}{2}°$	Carbon Bisulphide..38°
Alcohol......$47\frac{1}{2}$	Flint-glass......$36\frac{1}{2}$	Diamond..........$24\frac{1}{2}$

Total reflection can be illustrated by means of the optical disc.

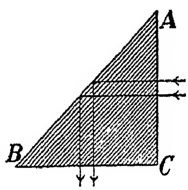


Fig. 444.—A total
tion prism.

407. Total-reflection prisms. Let *ABC* (Fig. 444) be a glass prism with well-polished faces, the angles *A* and *B* each being 45°, and *C* therefore 90°. If light enters as shown in the figure, the angle of incidence on the face *AB* is 45°, which is greater than the critical angle. It will, therefore, be totally reflected and pass out as indicated. Another form of total-reflecting prism is shown in Fig. 445 in which the angle *B* is 135°, *A* and *C* each $67\frac{1}{2}°$. The course of the light is shown. Such arrangements are the most perfect reflectors known and are frequently used in optical instruments, for example, in the the binocular (§ 451).

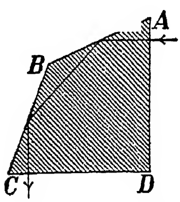


Fig. 445. — Another form of total-reflection prism.

This principle is also used in one form of the so-called "Luxfer" prisms, two patterns of which are shown in Fig. 446. They are firmly fastened in iron frames which are let into the pavement. The skylight enters from above, is reflected internally at the hypothenuse faces, and effectively illuminates the dark basement rooms.

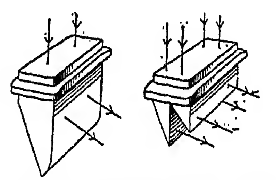


Fig. 446.—'Luxfer' prisms, useful in lighting basements.

408. Colladon's Fountain of Fire. Another beautiful illustration of total reflection is seen in the experiment known as Colladon's Fountain. A reservoir A (Fig. 447), about one foot in diameter and three feet high, is filled with water. Near the bottom is an opening B, about $\frac{1}{2}$ inch in diameter, from which the water spurts. A parallel beam of light from a lantern enters from behind, and by a lens C is converged to the opening from which the water escapes. The light enters the falling water, and, being incident at angles greater than the critical angle, it is totally reflected from side to side. The light imprisoned within the jet gives the water the appearance of liquid fire. Coloured glasses may be inserted at D, and beautify the effect.

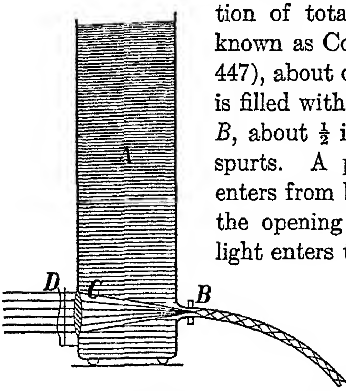


FIG. 447.—The 'fountain of fire.' The falling water seems to be on fire.

409. Refraction through Prisms. A prism, as used in optics, is a wedge-shaped portion of a refracting substance contained between two plane faces. The angle between the faces is called the **refracting angle,** and the line in which the faces meet is the **edge of the prism.**

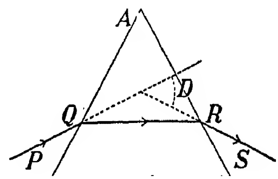


FIG. 448.—The path of light through a prism.

In Fig. 448 is shown a section of a prism, the refracting angle A of which is 60°, and $PQRS$ is a ray of light passing through it. The angle D between the original direction PQ and the final direction RS is the **angle of deviation.** The deviation is always **away from the edge of the prism.** When the light passes through the prism symmetrically, as in Fig. 448, in which the angle of emergence is equal to the angle of incidence, the deviation D is the smallest it can be, and the prism is said to be in the **position of minimum deviation.**

QUESTIONS AND PROBLEMS

1. A strip of glass is laid over a line on a paper (Fig. 449). When observed obliquely, the line appears broken. Explain why this is so.

2. A thick plate of glass is interposed obliquely between a lighted candle and the observer's eye. Will the apparent position of the candle be altered by the glass? Explain by means of a diagram.

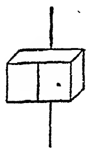


FIG. 449.—Why does the line appear broken?

3. When an empty test-tube is thrust into water and placed in an inclined position, the immersed part, when viewed from above, appears as if filled with mercury. If the tube is now filled with water, the brilliant reflection disappears. Explain this phenomenon.

4. If you hold a glass of water with a spoon in it above the level of the eye and look upward at the under surface of the water, you are unable to see the part of the spoon above the water, and the surface of the water appears burnished like silver. Explain.

5. Two experiments on total reflection:

(*a*) Arrange two total-reflection prisms to form a periscope.

(*b*) Show how to direct a ray of light into a total-reflection prism as in Fig. 444 so that it may emerge parallel to its original path.

6. Light passes through a 60° prism parallel to the base (as in Fig. 448). Find the angle of refraction at Q. Then draw the incident ray and also measure the angle of incidence (Index, 3/2).

FIG. 450.—The plane face is on the outside.

7. The illumination of a room by daylight depends to a great extent on the amount of sky-light which can enter. Show why a plate of prism glass, having a section as shown in Fig. 450 placed in the upper portion of a window in a store on a narrow street is more effective in illuminating the store than ordinary plate-glass.

8. The critical angle of a substance is 41°. By means of a drawing determine the index of refraction.

9. Describe what a fish under water can see. (Take into account total reflection.)

REFERENCES FOR FURTHER INFORMATION

WRIGHT, *Light*, Chapter 3. (Good experiments.)
EDSER, *Light for Students*, Chapter 3.
DUNCAN AND STARLING, *A Text Book of Physics*, Part III.

CHAPTER LXI

LENSES

410. Historical. Some ancient writers, such as Aristophanes, 425 B.C., speak of transparent stone being employed to kindle fires, and this has been interpreted as a "burning glass"; but the first authentic mention of the use of lenses occurs about 1280 A.D., and the reference is to spectacles designed to assist the eyesight of old people. At the present time lenses are used in spectacles, microscopes, telescopes, cameras and many other instruments. Although requiring great skill in their manufacture, millions are made every year, and they range in size from a pin-head to a cart-wheel.

411. Lenses. A lens is a portion of a transparent refracting medium bounded either by two curved surfaces or by one plane and one curved surface.

Almost without exception the medium used is glass, of which there are many kinds, and the curved surfaces are portions of spheres.

Lenses may be divided into two classes: (*a*) Convex or converging lenses, which are thicker at the centre than at the edge

(*b*) Concave or diverging lenses, which are at the centre than at the edge.

CONVERGING DIVERGING

Double- convex. Plano- convex. Concavo- convex. Double- concave. Plano- concave. Convexo- concave.

FIG. 451.—Lenses of different types.

In Fig. 451 are shown sections of different types of lenses. The concavo-convex lens is sometimes called a converging meniscus, and the convexo-concave a diverging meniscus. A meniscus is a cresent-shaped body.

412. Principal Axis. The principal axis is the straight line joining the centres of the spherical surfaces bounding the lens; or, if one surface is plane, it is the straight line drawn through the centre of the sphere and perpendicular to the plane surface.

413. Action of a Lens. The behaviour of the rays of light when they pass through a lens can be exhibited clearly by means of the optical disc. First, project the light through a double-convex lens, as in Fig. 452. It will be seen that the rays are bent towards the principal axis and converged to a point and then spread out. Next, use a double-concave lens, as in Fig. 453. In this case the rays diverge from the principal axis.

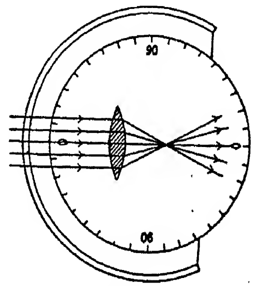


Fig. 452.—Action of a converging lens.

Similarly, we can show that all lenses which are thicker at the centre converge the rays of light while those which are thinner at the centre diverge the rays.

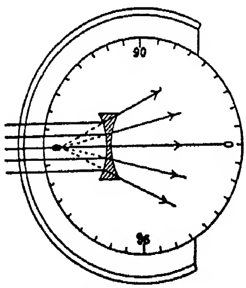


Fig. 453.—Action of a diverging lens.

The action of a convex lens may be compared to that of two prisms with their bases together (Fig. 454*a*), and the action of a concave lens to that of the prisms placed apex to apex (Fig. 454*b*).

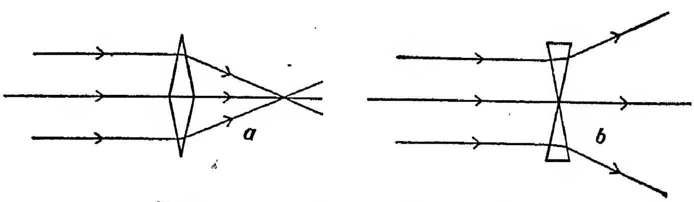


Fig. 454.—Comparison of lenses and prisms.

414. Principal Focus. Let rays parallel to the principal axis fall upon a convex lens (Fig. 455a). That ray which passes along the principal axis meets the surfaces at right angles, and hence passes through without suffering any deviation. But all other rays are bent from their original paths, the deviation being greater as we approach the edge. The result is, the rays are converged approximately to a point F on the principal axis.

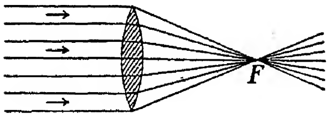


Fig. 455a.—Parallel rays converged to the principal focus F.

This point is called the **principal focus**, and in the case shown, since the rays actually pass through the point, it is a *real* focus.

A parallel beam, after passing through a concave lens (Fig. 455b) is spread out in such a way that the rays appear to come from F, which is the principal focus and which, in this case, is evidently *virtual.*

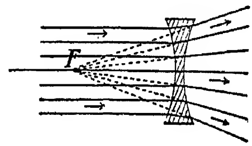


Fig. 455b.—In a diverging lens the principal focus F is virtual.

The **focal length** is the distance from the principal focus to the lens, or, more accurately, to the centre of the lens.

415. Conjugate Foci; Converging Lens. If the light is moving parallel to the principal axis and falls upon a convex lens, it is converged to the principal focus (Fig. 455a). Next, let it emanate from a point P, on the principal axis (Fig. 456). The lens now converges it to the point P', also on the principal axis and farther from the lens than F.

Fig. 456.—P and P' are conjugate foci.

Again, let us consider the direction of the light as reversed, that is, let it start from P' and pass through the lens. It is evident that it will now converge to P. Hence P and P' are

two points such that light coming from one is converged by the lens to the other. Such pairs of points are called **conjugate foci,** as in the case of curved mirrors. (§ 387).

As P is taken nearer the lens, its conjugate focus P' moves farther from it. If P is at F, the principal focus, the rays leave the lens parallel to the principal axis (Fig. 457), and when P is closer to the lens than F (Fig. 458), the lens con-

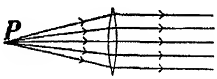


FIG. 457.—Light emanating from the principal focus.

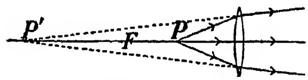


FIG. 458.—Here P', the focus conjugate to P is virtual.

verges the rays somewhat and they move off apparently from P' which in this case is a virtual focus.

416. Explanation by Means of Waves. The theory that light consists of waves easily accounts for the action of lenses. Let us suppose that waves of light travelling through the air pass through a glass lens.

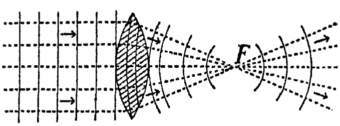


FIG. 459.—Plane waves made spherical by a converging lens.

In Fig. 459 plane waves (parallel rays) fall on the lens. Now their velocity in glass is only $\frac{2}{3}$ that in air, and that part of the waves which passes through the central part of the convex lens will be delayed behind that which traverses the lens near its edge, and the result is, the waves are concave on emerging from the lens. They continue moving onward, continually contracting, until they pass through F, the principal focus, and then they enlarge.

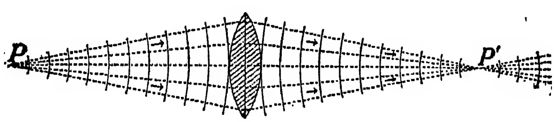


FIG. 460.—Waves expanding from P are changed by the lens into contracting spherical waves.

In Fig. 460 spherical waves spread out from P. On traversing the central portions they are held back by the thicker part of the lens, and

on emerging they are concave, but they do not converge as rapidly as in the first case.

417. Object and Image; Converging Lens. The following experiments on the relative positions of object and image are very important and if possible should be performed by every student. They are similar to those produced with a concave mirror (§ 389).

Experiments. (1) First place a convex lens in its holder on the table, and set a candle as far from it as possible (at the far end of the room). Then move a sheet of paper back and forth behind the lens until the small bright image is found. Examine it closely and you will see that it is inverted. The distance of the paper from the lens is its focal length (approximately).

Hold the lens in sunlight and move the paper until the very bright image of the sun is seen. The focal length can easily be measured. Hold the lens in the sunlight for some time. The great heat of the image will probably burn the paper. Such a lens is called a *burning-glass*.

(2) Now bring the candle slowly up toward the lens, at the same time moving the screen so as to keep the image on it. We find that the image gradually moves away from the lens, continually increasing in size as it does so.

At a certain position the image is of the same size as the object, but inverted. By measurement we find that each is twice the focal length of the lens from the lens.

(3) Bring the candle still nearer to the lens. The image retreats and is larger than the object, and when the candle is at the principal focus the image is at an infinite distance,—the rays leave the lens parallel to the principal axis.

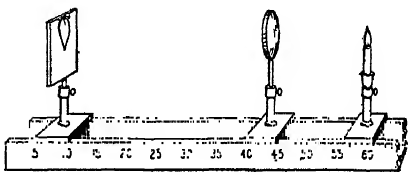


Fig. 461.—An optical bench, for studying object and image.

(4) Finally, hold the candle between the principal focus and the lens; no real image is formed (Fig. 458), but on looking through the lens one sees a virtual enlarged image of the object. Its position can be found by the method of parallax.

These results may be arranged in a table, as follows (f = focal length):

IMAGES WITH CONVERGING LENS

Position of Object	Position of Image	Real or Virtual	Size	Erect or Inverted
Far from lens.	Beyond but near F.	Real.	Smaller.	Inverted.
$2f$ from lens.	$2f$ from lens.	Real.	Same size.	Inverted.
Between $2f$ and f from lens.	Beyond $2f$ from lens.	Real.	Larger.	Inverted.
At F.	Rays parallel.			
Between F and lens.	On same side as object.	Virtual.	Larger.	Erect.

For making measurements of the distances of object and image from the lens, the most convenient arrangement is an optical bench, one form of which is shown in Fig. 461.

CHAPTER LXII

DIVERGING LENSES; APPLICATIONS OF LENSES

418. Conjugate Foci; Diverging Lens. In the case of a diverging lens, if the incident light is parallel to the principal axis, it leaves the lens diverging from the principal focus

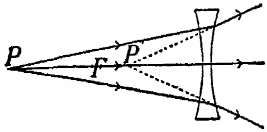


Fig. 462.—Conjugate foci in diverging lens.

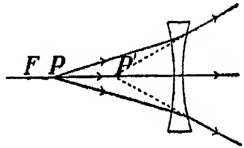


Fig. 463.—Conjugate foci in diverging lens.

F (Fig. 455b). Let the light start from the point P (Figs. 462, 463). The light is made still more divergent by the lens, and, on emergence from it, appears to move off from P', which is conjugate to P and is virtual.

419. Passage of Waves through a Concave Lens. In Fig. 464 is shown the effect of a concave lens upon the waves passing through it. The outer portions of the lens, being thicker than the central, retard the waves most, with the result that the convexity of the waves on emergence is increased, so that they move off having P' as their new centre.

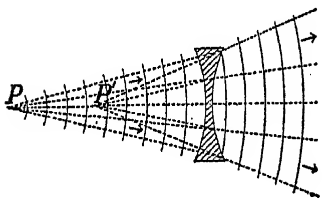


Fig. 464.—Waves going out from P are made more curved by the lens, and appear to have P' as their centre.

These results are further illustrated in a striking and beautiful manner by using an *air* lens in an *"atmosphere" of water.* Such a lens can be constructed without difficulty by cementing two "watch-glasses" into a turned wooden or ebonite rim. In Fig. 465 is shown a double-concave lens immersed in water contained in a tank with plate-glass sides.

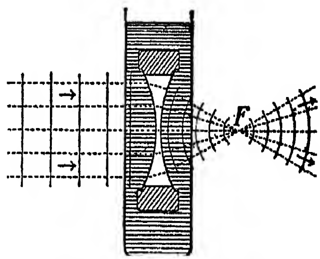


Fig. 465.—A concave air-lens in an atmosphere of water converges the light.

Plane waves from a lantern pass into the water, and on entering the lens the outer portions, since they travel in the air, rush forward ahead of the central part, thus rendering the waves concave and converging to a focus F. Thus a concave air-lens in water is converging; in a similar way it can be shown that a convex air-lens in a water atmosphere is diverging.

420. Object and Image; Diverging Lens. With a concave lens we cannot obtain a real image of the object. If we view the candle through a concave lens, we always see an erect image smaller than the candle, apparently between the lens and the candle. It is always virtual (see Figs. 462, 463). The position of the image can be found by means of the method of parallax. Stand a hat-pin or knitting-needle behind the lens so that it can be seen above the lens. Move it until no relative motion between it and the image can be detected when the head is moved from side to side. If we use a distant object, the focal length can be found at once. (Another method is given in § 429.)

421. How to Locate the Image by a Diagram. Let PQ (Fig. 466) be an object placed before a convex lens A. The position of the image can be very easily located in the following way.

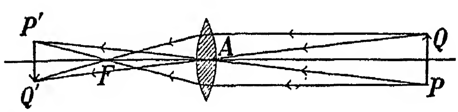


FIG. 466.—Showing how to locate the image of PQ.

From Q draw a ray parallel to the principal axis; on emerging from the lens it will pass through F, the principal focus. Again, the ray QA which passes through the centre of the lens is not changed in direction. Let it meet the former ray in Q'. Then Q' will be the point on the image corresponding to Q on the object. From P draw a ray parallel to the principal axis; after passing through the lens it will go through F. Also draw the ray PA. It will meet the former ray in P', which will be the image of P; and $P'Q'$ is the image of PQ. It is a real image.

If the object had been placed at $P'Q'$ the image would have been at PQ. (Make the diagram for this case.) $P'Q'$ and PQ are therefore conjugate foci.

Further examples of drawing images are given in §§ 423, 424.

422. A Simple Camera. The camera illustrates well the method of locating the image of an object. A simple form is illustrated in Fig. 467. There is a lens A in the front of a

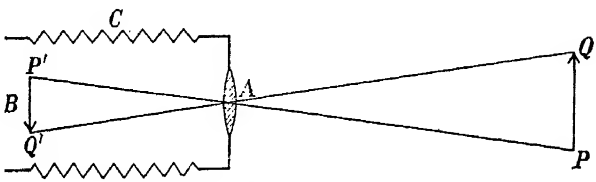


FIG. 467.—Diagram of a simple camera.

box and a sensitive film B at the back. Light from an object PQ passes through the lens and forms an image $P'Q'$. By means of the bellows C the distance of the film from the lens may be altered until the image is exactly on the film. The camera is then said to be focussed.

If the object is a long way off the image is approximately at the focus of the lens. Some box cameras cannot be focussed. This simply means that with such cameras only objects beyond a certain distance can be photographed. If the object is nearer, the image will not be accurately on the film and the picture will be blurred. For a near object the camera must be focussed.

423. Projection Lantern. In principle the projection lantern is similar to the camera. A convenient type of lantern is shown in Fig. 468 and a vertical section of it in Fig. 469. Its two essential parts are the source of light A and the projection lens, or set of lenses, D, which acts as a single convex lens in the manner described in § 421.

The source should be as intense as possible. (Why?) In the figure it is an incandescent electric lamp, but an arc lamp, an acetylene jet or a strong oil lamp may be used. The light

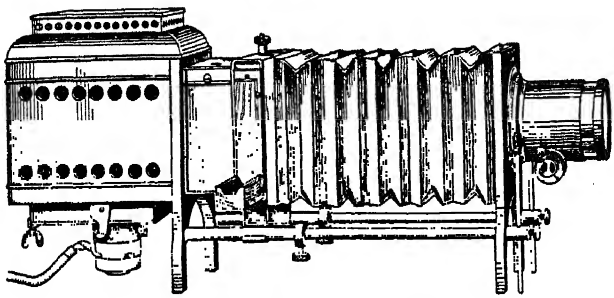


FIG. 468.—A projection lantern.

diverging from the source is directed by means of the so-called *condensing lenses* B upon the object C which we wish to exhibit on the screen E. This object is usually a photograph on glass, and is known as a lantern slide.

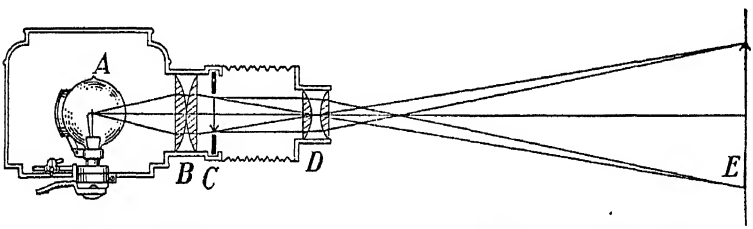


FIG. 469.—Vertical section of a projection lantern, showing how the image is produced on the screen.

In a tube is D, the projecting lens. By moving this nearer the slide or farther from it a real and much enlarged image of the picture on the slide is produced upon the screen. The slide and the screen are conjugate foci. As the image on the screen is erect, and since the projecting lens inverts the image, it is evident that the slide C must be placed in its carrier with the picture on it upside down.

424. Locating the Image: Other Cases. If the object is placed nearer to a convex lens than its principal focus the diagram to locate the image is that in Fig. 470.

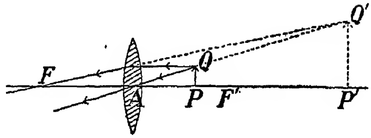


Fig. 470.—How to draw the image when the object is between the lens and the principal focus. The image is virtual.

The rays drawn parallel to the axis and through the centre of the lens do not meet after passing through the lens, but on producing them backwards they intersect at Q'. $Q'P'$ is the image of QP. It is virtual, erect and larger than the object. The image in a simple microscope is produced thus (see § 425).

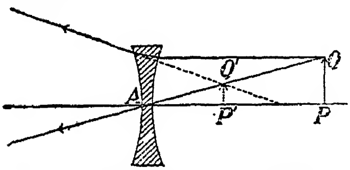


Fig. 471.—How to draw the image in a concave lens.

For a concave lens we have the construction shown in Fig. 471. The image is $P'Q'$. It is virtual, erect, and smaller than the object; and on the same side of the lens.

Relation between Distances of Object and Image. There is a simple formula connecting the distances of object and image from the lens.

Consider a concave lens and let the light be coming from right to left (Fig. 471). Let $AP = p$, $AP' = p'$, and $AF = f$. (Note that in this case, P, P' and F are all to the right of the lens.) Then it can be shown

that $1/p' - 1/p = 1/f$.*

This formula holds for all positions of object and image and also for a convex lens, if we denote all lengths measured to the right of A "+" and those measured to the left "−".

425. The Simple Microscope or Magnifying Glass. In order to see an object well, that is, to recognize details of it, we bring it near to the eye, but, as we know, when it gets within a certain distance the image is blurred. By placing a single convex lens before the eye we are enabled to bring the object quite close to the eye and still have the image of it in the eye distinct.

*A proof of this formula will be found in an appendix to the *Laboratory Manual* designed to accompany this work.

How this is done is shown in Fig. 472. (See also Figs. 470 and 474.) The object PQ is placed within the principal focus F. The image pq is virtual, erect and enlarged as in Fig. 470. The lens is moved back and forth until the image is focussed, in which case the image is at what is called the least distance of distinct vision from the eye, about 10 inches. The magnification is greatest when the eye is close to the lens.

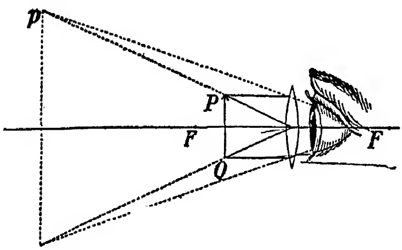


FIG. 472.—Illustrating the action of the simple microscope.

The rule for finding the **magnifying power** is: **Divide the least distance of distinct vision (10 in. or 25 cm.) by the focal length of the lens.** The proof of this is too difficult to be given here.*

For example, if the focal length is $\frac{1}{2}$-inch the magnifying power $= 10 \div \frac{1}{2} = 20$.

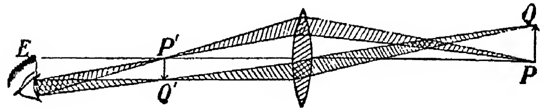
426. Magnification. On examining Figs. 466, 471, it will be seen that the triangles QAP, $Q'AP'$ are similar, and as before (§ 390), calling the ratio of the length of the image to that of the object the **magnification**, we have

$$\text{Magnification} = \frac{P'Q'}{PQ} = \frac{\text{distance of image from lens}}{\text{distance of object from lens}}.$$

427. Vision Through a Lens. In §§ 421, 424 is explained a method of finding the position of an image produced by a lens, but it should be remembered that this is simply a geometrical construction and that the rays shown there are usually not those by which the eye sees the image. Let us draw the rays which actually enter the eye.

*See CHANT AND BURTON, *College Physics*, p. 517.

In Fig. 473 $P'Q'$ is the (real) image of PQ, and E is the eye. From Q' draw rays to fill the pupil of the eye. Then produce these backwards to meet the lens and finally join them to Q. Thus we obtain the pencil by which Q is seen.



. 473.—Showing the rays by which the eye sees the image of an object.

In the same way we trace the light from P to the eye.

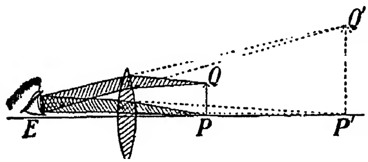


FIG. 474.—The rays reach the eye by the paths shown.

In Fig. 474 $P'Q'$ is virtual, but the construction is the same as before. The student should draw other cases. The method is similar to that explained for curved mirrors (§ 396).

Exercise. Draw the rays by which the eye sees an object viewed through a concave lens.

428. Focal Length and Power of a Lens. Let us take two convex lenses and hold them in the light from the sun or from a lamp at the far end of the room. The light is converged to a point, in one case, let us suppose, 3 inches from the lens, in the other, 6 inches from the lens. The first lens converges the light more quickly than the second and we say that it is the stronger lens or the more powerful of the two. In other words, the more converging a lens is, the more powerful it is; or, the shorter the focal length, the greater is the power of a lens.

Similarly with a diverging lens. The more rapidly it spreads the light, the shorter is the focal length and the greater is the power of the lens.

The lens with a focal length of 3 inches has twice the power of that with a focal length of 6 inches.

In connection with the work of examining the eyes and prescribing spectacles a word has been coined to express the power of a lens. A lens with a focal length of 1m. or 100 cm. is said to have a power of 1 **dioptre.** If the focal length is $\frac{1}{2}$ m. or 50 cm., the power is 2 dioptres; if $\frac{1}{10}$ m. or 10 cm., the power is 10 dioptres; and so on.

We may express the relation between power and focal length thus:

$$\text{Power in dioptres} = \frac{100}{f \text{ in cm.}}.$$

For example if $f = 20$ cm., $P = 5$ dioptres,

$f = 40$ cm., $P = 2{\cdot}5$ dioptes.

Also, if we know the power of a lens we can calculate its focal length.

For example, if $P = 4$ dioptres, $f = 100/P = 25$ cm.

A converging lens is considered to be positive and is marked "+"; a diverging lens negative and is marked "$-$".

In prescribing spectacles the oculist states in dioptres the powers of the lenses required.

429. Combinations of Lenses. Consider two converging lenses placed close together (Fig. 475). Let their focal lengths be f_1, f_2 and their powers be P_1, P_2. The first lens alone would converge the light to F_1, and the second, adding its converging power, brings the light to F. It is evident that we can add the two powers together and the total power of the combination is $P_1 + P_2$.

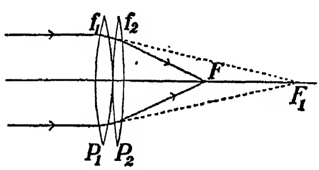


FIG. 475.—Combination of two converging lenses.

For example, let $f_1 = 20$ cm. and $f_2 = 25$ cm.

Then $P_1 = +5$ dioptres and $P_2 = +4$ dioptres,

and the power of the combination $= +9$ dioptres.

Hence the focal length of the combination $= \frac{100}{9} = 11\frac{1}{9}$ cm.

Next, consider the combined action of a convex and a concave lens (Fig. 476).

Let $f_1 = 20$ cm. (converging lens) and $f_2 = 25$ cm. (diverging lens).

Then $P_1 = +5$ dioptres and $P_2 = -4$ dioptres, and the power of the combination $= +1$ dioptre. Also, the focal length of the combination $= 100/1 = 100$ cm.

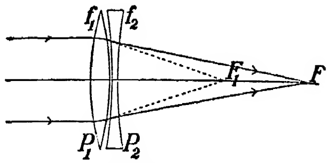


FIG. 476.—Combination of a converging and a diverging lens.

It is clear that if we know the focal length of the converging lens and measure the focal length of the combination we can deduce the focal length of the diverging lens. To use this method the power of the converging lens should be considerably greater than that of the diverging lens.

QUESTIONS AND PROBLEMS

1. Draw sections of three different types of converging lenses and of three diverging lenses.

2. Explain with diagrams what is meant by the principal focus and the focal length of a converging lens and of a diverging lens.

3. With the aid of diagrams explain what is meant by conjugate foci in the case of a convex lens and also of a concave lens.

4. An object is placed 60, 40, 20 cm. from a convex lens of focal length 30 cm. Make three diagrams showing the position, nature and size of the image in each case.

5. A candle is placed 20 cm. from (*a*) a convex lens of focal length 10 cm., and (*b*) a concave lens of focal length 30 cm. Make a diagram, approximately to scale, in each case, showing how and where the image is produced.

6. A plane mirror is placed behind a convex lens and a candle is at the principal focus in front. Where is the image?

7. A candle is 2 m. from a screen. A convex lens placed 40 cm. from the candle throws an image of the candle on the screen. Show that there is another place where the candle may be placed to throw an image on the screen. What is the magnification in the two cases? Draw a diagram in the first case and by geometry find the focal length of the lens.

8. A projection lantern throws upon a screen an image of an object 2 inches high on a lantern slide which is placed in the lantern 10 inches from the projecting lens. If the screen is 30 feet from the lens what is the height of the image on the screen? (Make a clear diagram.)

9. The mercury column in a thermometer looks much wider than it actually is. Explain why.

10. A camera is focussed for a distant object. If you wish to focus on a near-by object, will you move the lens in or out?

11. If you wished to get a powerful burning glass, what would you ask for, (*a*) as to diameter, (*b*) as to focal length? Explain.

12. An oculist prescribed spectacles with powers of +2·00 dioptres for the right and +3·00 dioptres for the left eye. Find the focal lengths of these lenses.

13. In another case the prescription was −4·50 for the right and −2·50 for the left eye. Find the focal lengths. (The minus sign means that the lenses were negative or diverging. Such are used for short-sightedness.)

14. The main lens of a telescope is composed of two lenses close together: one converging, of focal length 75 cm.; the other diverging, of focal length 200 cm. Find the focal length of the compound lens.

15. Some telescope lenses are made up of three components close together, there being a diverging lens on each side of the converging one. If the focal length of the converging lens is 150 cm. and that of each of the others is 500 cm., find the focal length of the combination.

REFERENCES FOR FURTHER INFORMATION

EDSER, *Light for Students*, Chapter 3.
NIGHTINGALE, *Heat, Light and Sound*, Chapter 17.
ENCYCLOPEDIA BRITANNICA, Articles on *Lens*, *Telescope*.

CHAPTER LXIII

DISPERSION, COLOUR

430. Newton's Experiment. About 1668 Newton made a famous experiment (Fig. 477). He admitted sunlight through a hole in a window-shutter, and placed a glass prism in the path of the beam. On the opposite wall, $18\frac{1}{2}$ feet from the prism, he observed an oblong image, which had parallel sides and semi-circular ends, $2\frac{1}{8}$ inches wide and $10\frac{1}{4}$ inches long. That end of the image farthest from the original direction of the light was violet, the other end red.

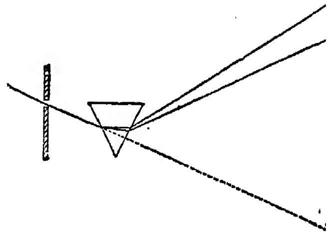


FIG 477.—Diagram illustrating Newton's production of the spectrum.

This image Newton called the spectrum. He thought he could recognize seven distinct colours, which he named in order: red, orange, yellow, green, blue, indigo, violet.

It should be noted, however, that there are not seven separate coloured bands with definitely marked dividing lines between them. The adjoining colours blend into each other, and it is impossible to say where one ends and the next begins. Very often indigo is omitted from the list of colours, as not being distinct from blue and violet.

From Newton's experiment we conclude:

(1) That white light is not simple but composite, and includes constituents of many colours.

(2) That these colours may be separated by passing the light through a prism.

(3) That lights which differ in colour differ also in degrees of refrangibility, violet being refracted most and red leas

The separation, or *spreading out*, of the constituents of a beam of light is called dispersion.

It is generally assumed that light travels in the form of waves (see § 360 and also § 613). The length of the waves of red light are nearly twice as long as those of violet light and those of the other colours range between. They are all extremely small, the wave-length of the deepest red being $\frac{1}{30000}$ inch. The short waves are refracted more than the long ones and in this way the colours are dispersed.

It will now be understood why, in § 401, when giving the indices of refraction for various substances, it was necessary to specify to what colour the values referred.

431. A Pure Spectrum. It is often inconvenient to use sunlight for this experiment, but we may substitute for it the light from a projecting lantern.

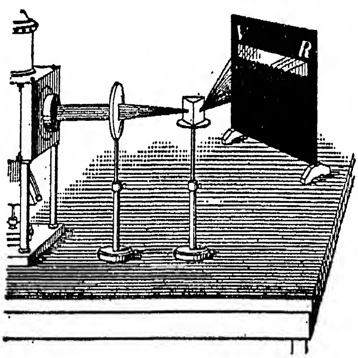


FIG. 478.—Showing how to produce a pure spectrum.

A suitable arrangement is illustrated in Fig. 478. The light emerges from a narrow vertical slit in the nozzle of the lantern, and then passes through a converging lens, so placed that an image of the slit is produced as far away as is the screen on which we wish to have the spectrum. Then a prism is placed in the path, and the spectrum appears on the screen.

For this experiment the projection lantern described in § 423 may conveniently be used. The slit may be made by pasting strips of dark paper on a piece of glass which is then put in the slide carrier. The projecting lens of the lantern takes the place of the lens on a stand in Fig. 478.

The spectrum thus produced is *purer* than that obtained by Newton's simple method. Imagine the round hole used by Newton to be divided into narrow strips parallel to the

edge of the prism. Each strip produces a spectrum of its own, but the successive spectra overlap, and hence the colour produced at any place is a mixture of adjacent spectral colours. Thus, to obtain a **pure spectrum, that is, one in which the colours are not mixtures of several colours,** we require a narrow slit as our source, and the narrower the slit the purer the spectrum. In addition, a lens must be used to focus the image of the slit on the screen, and the prism should be placed in the position of minimum deviation (§ 409).

Let us produce the spectrum on the screen by means of the projecting lamp; we obtain all the colours as in *a*, Fig. 479. Next, place over the slit a red glass; the beam now transmitted consists mainly of red light, a little orange perhaps being present (*b*, Fig. 479). The glass does not owe its colour to the introduction of anything into the spectrum which did not previously exist there, but simply because it absorbs or suppresses all but the red and a little orange. We obtain similar results with green, yellow, or other colours. It is to be noted, however, that scarcely any of the transmitted colours are pure. Several colours will usually be found present, the predominating one giving its colour to the glass.

FIG. 479.—A red glass transmits only red and some orange.

The transmission of light by glasses of different colours will be made clearer by the adjoining diagrams (Figs. 480, 481, 482). Let us think of white light being made up of six constituents or parts, *v*, *b*, *g*, *y*, *o*, *r*, and

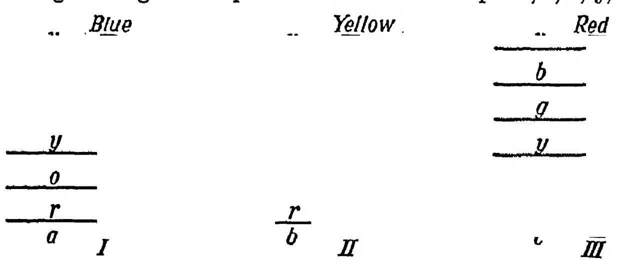


FIG. 480.—Transmission of light by different coloured glasses.

let them come up to a blue glass (Fig. 480*a*). This glass we may think of as a filter or a "gate", which we shall call number I. Part *b* passes through in almost full strength, while the neighbouring parts *g* and *v* get through but somewhat weakened. "Gate" II (Fig. 480*b*) is a yellow glass. The yellow part of the white light gets through in almost full strength, and to some degree parts *o* and *g* pass through. "Gate" III is a red glass. It allows red in full strength and also some of orange to pass through (Fig. 480*c*).

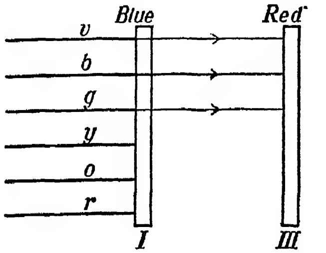


Fig. 481.—Combination of blue and red glasses—darkness.

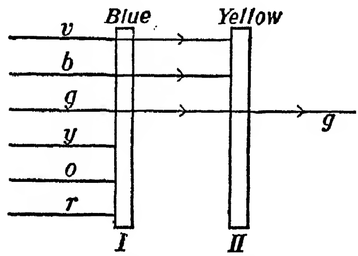


Fig. 482.—Combination of blue and yellow—green.

Next let us try to pass white light through I and III, as in Fig. 481. Through I passes *b* and some of *g* and *v*, but these cannot get through III at all. These two "gates" shut out the light completely. Finally let us combine I and II (Fig. 482). We see that some green but nothing else gets through both. If you look at a white light through blue and yellow glasses, one behind the other, the light will appear green.

It may be well to state here that there is something beyond the red and the violet in the spectrum, which we call the infra-red and the ultra-violet components. The former is used in infra-red photography and the latter is of great importance to our health. These things are discussed in Chapter LXXXIV.

433. Colours of Natural Objects. Now let us hold a bit of red paper or ribbon in different portions of the spectrum. In the red it appears of its natural colour, but in every other portion it looks black. This tells us that a *red* object appears red because it absorbs the light of all other colours, reflecting or scattering only the red. In order to produce this absorption and scattering, however, the light must penetrate some distance into the object; it is not a simple surface effect. Similarly with green, or blue, or violet ribbons; but, as in

the case of the coloured glass, the colours will usually be far from pure. Thus a blue ribbon will ordinarily reflect some of the violet and the green, though it will probably appear quite black in the red light.

Let us consider for a moment what happens when sunlight falls on various natural objects. The rose and the poppy appear red because they reflect mainly red light, absorbing the more refrangible colours of the spectrum. Leaves and grass appear green because they contain a green colouring matter (chlorophyll), which is able largely to absorb the red, blue and violet, the sum of the remainder being a somewhat yellowish green. A lily appears white because it reflects all the component colours of white light. When illuminated by red light it appears red; by blue, blue.

A striking way to exhibit this absorption effect is by using a strong sodium flame in a well-darkened room. This light is pure yellow, and bodies of all other colours when illuminated by it appear black. The flesh tints are entirely absent from the face and the hands which therefore present a ghastly appearance.

We see, then, that the colour which a body exhibits depends not only on the nature of the body itself, but also upon the nature of the light by which it is seen.

At sunrise and sunset the sun and the bright clouds near it take on gorgeous red and golden tints. These are due chiefly to absorption, not to refraction. At such times the sun's rays, in order to reach us, have to traverse a greater thickness of the earth's atmosphere than they do when the sun is overhead and the shorter light-waves, which form the blue end of the spectrum, are more absorbed than the red and yellow, which tints therefore predominate.

In § 299 reference was made to the stupendous volcanic eruption at Krakatoa in 1883. For many weeks after this the atmosphere was filled with dust, and sunsets of extraordinary magnificence were observed over the world. Somewhat similar absorption effects are produced in the neighbourhood of great forest fires, the ashes from which are conveyed by winds over considerable areas.

434. Recomposition of White Light. We have considered the decomposition of white light into its constituents. The following experiments give several ways of performing the reverse operation of recombining the various spectrum colours into white light.

Experiments. (1) If two similar prisms be placed as shown in Fig. 483, the second prism simply reverses the action of the first and restores white light. The two prisms, indeed, act like a thick plate (§ 404).

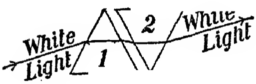


FIG. 483.—The secon prism counteracts the first.

(2) By means of a large convex lens, preferably a cylindrical one (a tall beaker filled with water answers well), the light dispersed by a prism may be converged and united again. The image, when properly focussed, will be white.

(3) Next, we may allow the dispersed light to fall upon several small plane mirrors, and these, if adjusted properly, will reflect the various colours to one place on the screen, which then appears white (Fig. 484).

(4) In place of the several small mirrors we may advantageously use a single strip of thin plate-glass mirror, say 2 feet long by 4 inches wide. First, hold this in the path of the dispersed light so as to reflect it upon the opposite wall of the room. Then, by taking hold of the two ends of the strip, gently bend it until it becomes concave enough to converge the various coloured rays to a spot on the screen.

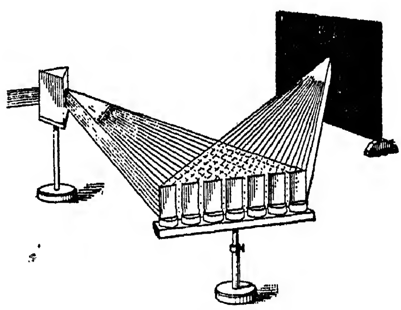


FIG. 484.—The light after passing through the prism falls on several small mirrors which reflect it to one place on the screen.

(5) In all the foregoing cases the coloured lights are mixed together outside the eye. Each colour gives rise to a colour-sensation, and a method will now be explained whereby the various colour-sensations are combined within the eye. The most convenient method is by means of Newton's disc, which consists of a circular disc of cardboard on which are pasted sectors of coloured paper, the tints and the sizes of the sectors being chosen so as to correspond as nearly as possible to the coloured bands of the spectrum.

Now put the disc on a whirling machine (Fig. 485) and set it in rapid rotation. It appears white, or whitish-gray. This is explained as follows:

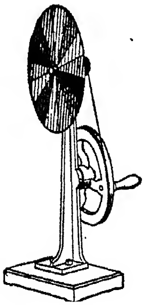


Fig. 485.—Newton's disc on a rotating machine.

Luminous impressions on the retina do not vanish instantly when the source which excites the sensation is removed. The average duration of the impression is $\frac{1}{10}$ second, but it varies with different people and with the intensity of the impression. If one looks closely at an incandescent electric lamp for some time, and then closes his eyes, the impression will stay for some time, perhaps for a minute. With an intense light it will last longer still.

If a live coal on the end of a stick is whirled about, it appears as a luminous circle; and the streak in the sky produced by a "shooting star" or by a rising rocket is due to this persistence of luminous impressions. In the same way, we cannot detect the individual spokes of a rapidly rotating wheel, but if illuminated by an electric spark, we see them distinctly. The duration of the spark is so short that the wheel does not move appreciably while it is illuminated.

In the familiar "moving pictures" the intervals between the successive pictures are about $\frac{1}{40}$ second, and the continuity of the motion is perfect.

If then the disc is rotated with sufficient rapidity, the impression produced by one colour does not vanish before those produced by other colours are received on the same portion of retina. In this way the impressions from all colours are present on the retina at the same time, and they make the disc appear of a uniform whitish-gray. This gray is a mixture of white and black, no colour being present, and the stronger the light falling on the disc the more nearly does it approach pure white.

Colours. Let us cut out of black cardboard a disc of the shape shown in Fig. 486, and fasten it on the axis of the whirling machine over the Newton's disc so that it just hides the red sectors. Rotate it; the colours which are exposed produce a bluish-green. It is evident, then, that this colour and red when added together will give white. Any two colours which by their union produce white light are called complementary. From the way it was produced we know that this blue-green is not a

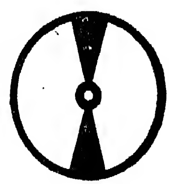


Fig. 486.—Disc to be put over Newton's disc to cut out any desired colour.

pure colour, but the eye cannot distinguish it from a blue-green of the same tint chosen from a pure spectrum. By covering over other colours of the Newton's disc we obtain other complementary pairs. A few of these pairs are given in the following table:

Complementary Colours

Red	Orange	Yellow	Green-yellow	Green
Bluish-green	Green-blue	Blue	Violet	Purple

In Fig. 487 these are arranged about a circle. Note that the complement of green is purple, which is not a simple spectral colour but a compound of red and violet.

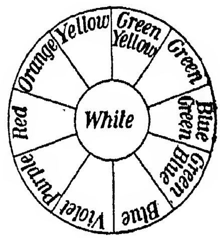


Fig. 487.—The radially opposite colours are complementary.

436. Mixture of Pigments. On rotating a disc with yellow and blue sectors,* as indicated in Fig. 488, we obtain white. On the other hand, if we mix together yellow and blue pigments, we get a green pigment. Wherein is the difference? It arises from the fact that the mixing of coloured lights is a true *addition* of the separate effects, while in mixing pigments there is a *subtraction* or *absorption* of the constituents of the light which falls on them.

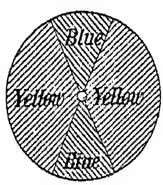


Fig. 488.—A complementary colour disc.

Ordinarily, blue paint absorbs the red and the yellow from the incident light, reflecting the blue and some of the adjacent colours, namely green and violet. Yellow paint absorbs all but the yellow and some orange and green. Hence, when yellow and blue paints are mixed, the only coloured constituent of the incident light which is not absorbed is green, and so the resulting effect is green. This is similar to passing white light through blue and yellow glasses—only green gets through (see § 432, Fig. 482).

*We might use a single sector of blue and one of yellow, but the speed of rotation would then have to be doubled.

Thus, mixing pigments and mixing colours are processes entirely unlike in nature, and we should not be surprised if the results produced are quite dissimilar. Indeed, the result obtained on mixing two pigments does not even suggest what will happen when two coloured lights of the same name are added together.

QUESTIONS AND PROBLEMS

1. In Newton's experiment (§ 430, Fig. 477), if the prism is removed, what would be seen on the opposite wall? Of what shape would the image be? Does this depend on the shape of the hole in the shutter? (§ 358.)

Newton says the spectrum on the wall had semi-circular ends. Why was that?

2. Name the colours which Newton thought were comprised in white light.

3. What is meant by the dispersion of light?

4. What experimental conditions must be observed in order to produce a pure spectrum on a screen?

5. Sunlight comes through a vertical crack in the wall of a darkened room and an observer looks at the crack through a prism with its edge vertical. Draw a horizontal section through the prism and crack showing the path of the rays from the crack to the eye of the observer, and also where the crack appears to him. Mark the colours of the image.

6. One piece of glass appears dark red and another dark green. On holding them together you cannot see through them at all. Why is this?

7. Light enters a room through a red glass; what colour will a blue dress appear in it?

8. A ribbon purchased in daylight appeared blue, but when seen by gas-light it looked greenish. Explain this.

9. Why is it hard to distinguish between navy blue and black by candle-light.

10. Explain from the physical point of view why a rose is red, a lily is white and charcoal is black.

11. If in a dark room one's hand or face is illuminated by sodium light it has a ghastly appearance. Explain why.

12. Account for the brilliant colours seen at sunrise and sunset.

13. What is meant by complementary colours? What is the colour complementary to yellow? to green?

14. Is white a colour? Is black?

CHAPTER LXIV

THE SPECTROSCOPE, THE RAINBOW

437. The Spectroscope. This is an instrument especially designed to examine the spectra of various sources. A simple

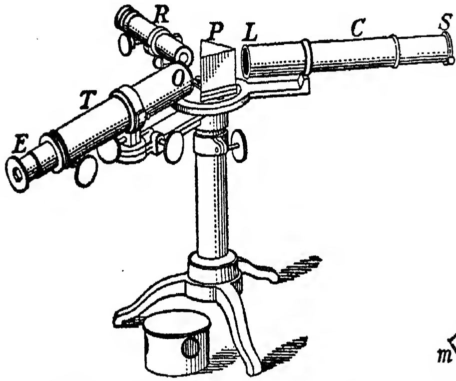


FIG. 489.—A single-prism spectroscope.

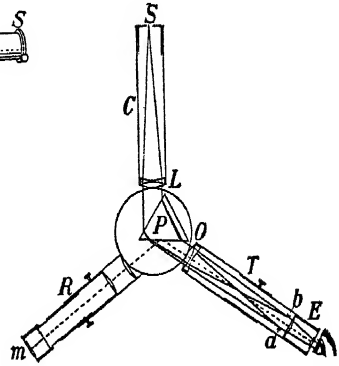


FIG. 490.—A horizontal section of a single-prism spectroscope.

form is illustrated in Fig. 489 and a sectional plan is given in Fig. 490. The tube C, known as the collimator, has a slit S at one end and a lens L at the other. The slit is at the focus of the lens, so that the light emerging from the tube is a parallel beam. It then passes through the prism P, and is received in a telescope T, the lens O of which focusses the spectrum in the plane ab. It is then viewed by the eyepiece E which acts as a simple microscope (§ 425).

The light to be examined is placed before S. Usually a third tube R, is added. This has a small transparent scale m at one end and a lens at the other. A lamp is placed before the scale, and the light passes through the tube, is reflected from a face of the prism and then enters the telescope, an image of the scale being produced at ab, above the spectrum. By means of this scale any peculiarities of the spectrum of the light which is under examination can be localized or identified.

Sometimes the telescope T can be removed and be replaced by a camera which photographs the spectrum. The instrument is then called a **spectrograph** and the photograph is called a **spectrogram.**

438. Direct-vision Spectroscope. If one uses three prisms, one of flint and two of crown-glass (Fig. 491), it is possible to get rid of the deviation of the middle rays of the spectrum while still dispersing the colours. Such a combination is used in pocket spectroscopes. The slit S admits the light and a convex lens converts the light into a parallel beam, which, after traversing the prisms, is seen by the eye at E. One tube can be slid over the other in order to focus the slit for the eye.

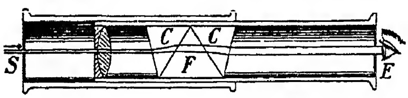


Fig. 491.—A direct-vision spectroscope.

439. Kinds of Spectra. By means of our spectroscope let us investigate the nature of the spectra given by various sources of light.

I. First, take an electric light. It gives a continuous coloured band, extending from red to violet without a break. A gas-flame, or an oil lamp gives a precisely similar spectrum. This is called a **continuous** spectrum.

II. Next, place a colourless Bunsen or alcohol flame before the slit, and in it burn some salt of sodium, chloride or carbonate of sodium, for instance. This may be done by dipping asbestos or a platinum wire in the solution and holding it in the flame. The flame is now bright yellow, and the spectrum shown in the spectroscope is a single bright yellow line.* Strontium nitrate produces a crimson flame, and the spectrum consists of several red and orange lines and a blue one. The salts of barium, potassium and other metals

*There are really *two* narrow lines very close together, which can be seen even with some pocket spectroscopes.

give similar results, each, however, with its own particular arrangement of lines.

If an electrical discharge is sent through a glass tube like that in Fig. 492 containing a gas under low pressure, and

A

Fig. 492.—An electrical discharge tube.

the narrow part A is presented to the slit of the spectroscope, a beautiful spectrum of bright lines is observed. Small neon and argon lamps working on a 110-volt circuit also give fine spectra.

Such are **discontinuous** or **bright-line** spectra.

III. Again, place an electric lamp before the slit of the instrument, and then between it and the slit place a glass vessel containing a dilute solution of permanganate of potash. The spectrum is now continuous except that it is crossed by fine dark bands in the green. Using a dilute solution of human blood, we get a continuous spectrum except for well-marked dark bands in the yellow and the green. Also try a piece of red glass. There will be a band in the red extending into the orange. These are **absorption** spectra.

440. Spectrum Analysis. Now each element, when in the form of a vapour, has its own peculiar spectrum, the arrangement of the bright lines in no two spectra being exactly alike. Hence, by means of its spectrum the presence of a substance can be recognized. If several elements are present, their spectra will all be shown and the elements can be thus recognized. This method of detecting the presence of an element is known as **spectrum analysis.** It is an extremely sensitive method of analysis.

In recent years the method has been so extended and perfected that it is possible, from the spectrograms taken, to estimate the minute quantity of metals present in a given substance with much less labour than would be required for

a chemical analysis. There are many applications in industry and in medical investigations.

441. The Solar Spectrum. On turning the spectroscope towards the sun, or reflecting sunlight into it, we find that the spectrum of sunlight consists of a bright band crossed by many dark lines. Fraunhofer* studied these and named the chief lines A, a, B, C, D, E, b, F, G, (Fig. 493) but they are all known as *Fraunhofer's lines*. They always have the same position in the spectrum.

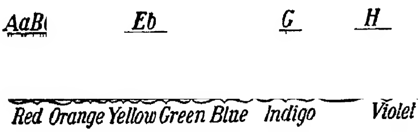


FIG. 493.—Showing some of the 'dark lines' in the spectrum of sunlight.

Photography has revealed at least 20,000 of these lines. For years attempts were made to find out the meaning of them, and in 1859 the mystery was solved by Kirchhoff.

In the orange-yellow of the solar spectrum is a prominent dark line—or rather a pair of lines very close together—named D by Fraunhofer. Now sodium vapour shows two fine bright yellow lines in exactly the same place in the spectrum. Surely there is some connection between sodium and the sun! The following experiment will suggest what it is.

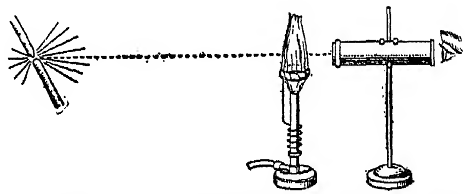


FIG. 494 ___ from the arc lamp passes through sodium vapour in the Bunsen flame and is then examined by the spectroscope. A dark band in the yellow is seen. The sodium vapour comes from the asbestos wick which has been soaked in a strong solution of common salt and is then held in the Bunsen flame.

First, place before the slit of the spectroscope an intense source of light, such as the arc light (Fig. 494). This gives a continuous spectrum with no dark lines at all. Now, while observing this, introduce between the arc light and the slit a Bunsen flame full of sodium vapour. This addition of yellow light we should naturally expect to make the yellow portion

*Fraunhofer (1787-1826) constructed his own prism and telescope, and engraved his own spectrum maps when he published his investigations in 1815.

of our spectrum more intense, but that is not at all what happens. On the contrary, we see two *dark lines* in precisely the position where the bright sodium lines are produced. If one thrusts an opaque screen between the arc light and the sodium flame the two bright lines due to sodium are seen.

442. Explanation of the Sun and Stars. Now, the inner portion of the sun corresponds to the arc light. It is intensely hot and would undoubtedly produce a continuous spectrum. The Bunsen flame corresponds to the atmosphere of the sun, in which, it would appear, there are vapours of sodium and other substances. These absorb some of the light from within and produce the dark lines.

It has been shown that sodium, iron, calcium, hydrogen, silver, titanium and about 50 more of the 92 chemical elements certainly exist in the sun's

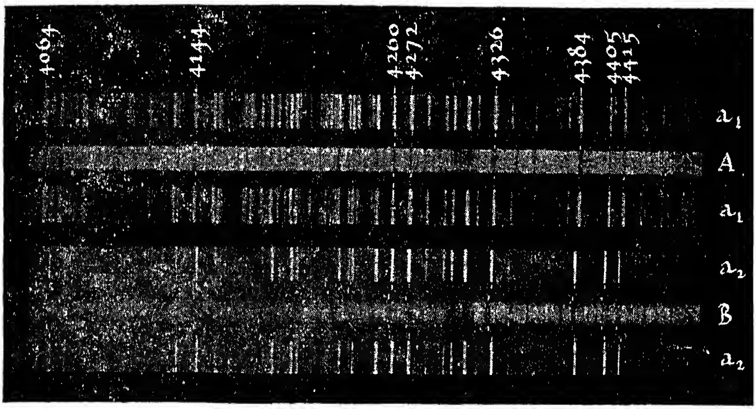


Fig. 495.—Spectrum of the Sun and a Star
(Photographed at the David Dunlap Observatory)

The strip *A* is the spectrum of the Sun, *B* that of the star known as Epsilon in the constellation of Andromeda. The strips a_1, a_1 and a_2, a_2 are the spectra of the vapour of iron. The numbers at the top gives the wave-lengths of the lines to which they are opposite (see § 613 and fol.).

First, compare the dark cross-lines in *A* with those in *B*. It is seen that both sets are arranged according to the same pattern, from which we conclude that the star is similar in nature to our sun, although it is 6,000,000 times as far away. *Second*, compare the marked lines in a_1 with those in *A*. They (as well as others) agree exactly and we conclude that there is iron in the sun. *Third*, compare the marked lines in a_2 and *B*. There is also iron in the star, but observe that the lines in *B* are displaced slightly to the left as compared with the lines in a_2. Measurement of this displacement, or shift, allows us to conclude that when this photograph was taken the star and the earth were approaching each other at the rate of 109 km. per sec. Of this amount the earth moving in its orbit contributes 23 and the star 86, that is, the star is approaching the solar system at 86 km., or 54 mi., per sec.

atmosphere. Others will probably be recognized in coming years. In 1868, observations showed the presence in the sun of a gas which was given the name *helium*, which means "solar substance," and in 1895 the chemist, Ramsay, discovered it on the earth. It is found along with natural gas, and is especially plentiful in some oil wells in Texas and Oklahoma.

By means of the spectroscope the astronomer has been able to show that the stars in the depths of space are composed of the same elements as the earth. In Fig. 495 are two photographs, one of the spectrum of the sun and the other of a faint star known as Epsilon in the constellation of Andromeda. These are on a larger scale than those in Plate 28, facing p. 452. The central bands A and B are the spectra of the sun and the star; the other sets of separate lines, a_1, a_1, and a_2, a_2, are the spectrum of iron photographed on the plate as "comparison lines," for the purpose of helping to find the relative positions of the lines in the other spectra. From the lines in the spectra it is possible to determine the chemical elements in the heavenly bodies, and it can be seen that the elements in the star are the same as in the sun. A further study of the stellar lines shows that their lines are displaced toward the blue end of the spectrum, and from this displacement it can be shown that the star is approaching the earth at the rate of 109 km. or 68 mi. per sec.* From a large number of stars it has been shown that our whole solar system is moving through space almost towards the bright star Vega at the rate of 12 mi. per second.

443. The Rainbow. In the rainbow we have a solar spectrum on a grand scale. It is produced through the refraction and dispersion of sunlight by raindrops. In order to see it the observer must look towards falling rain, with the sun behind him and not more than 42° above the horizon. Frequently two bows are visible, the **primary**

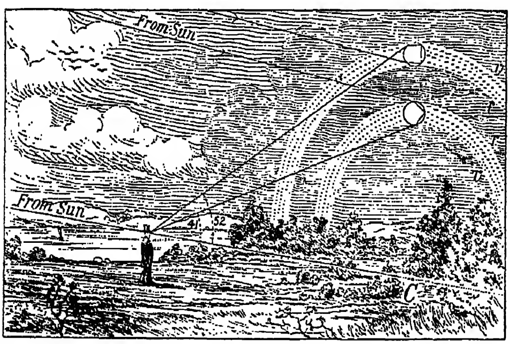


Fig. 496.—Illustrating how the rainbow is produced.

*This computation is based on Doppler's Principle, for an explanation of which one may consult Edser's *Light for Students*, p. 350. See also § 347 above.

bow and the **secondary** bow. The former is violet on the inside and red on the outside; while in the secondary bow, which is larger and fainter, the order of the colours is reversed. Both bows are arcs of circles having a common centre (C, Fig. 496), which is on the line which passes through the sun and the eye of the observer.

A line drawn from the eye to the primary bow makes an angle of about 41° with this line, while a line to the secondary bow makes an angle of about 52° with it.

Fig. 496 shows the relative positions of the sun, the raindrops and the observer. Fig. 497 shows the manner in which the sun's rays pass through the drops to form the primary bow. A ray of white light from the sun enters the drop at A and is broken up into its different colours, the violet rays being most refracted. The rays are all reflected internally (though not *totally* reflected) at B; and at C they are refracted out into the air, forming a diverging pencil.

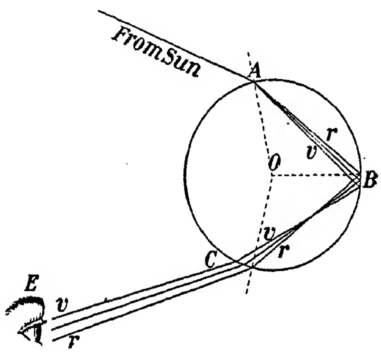


FIG. 497.—Showing how the light passes to form the primary bow.

Fig. 498 shows how the observer sees the different colours. Consider a series of drops arranged in the vertical line AB. The red rays from the highest drop come in greatest strength when it is in the position shown, that is, when a line from the eye to the drop makes an angle of 42° with a line from the sun to the drop (see the diagram). The violet rays from this particular drop pass over the observer's head, as shown in the figure. The violet rays get to the eye from the drop in the lowest position, that is, when a line from the eye to it makes an angle of 40° with the line from the sun. The red rays from this drop pass below the observer's eye. The

other drops between these two supply the intermediate colours. Thus the red rays are highest in the sky, or on the

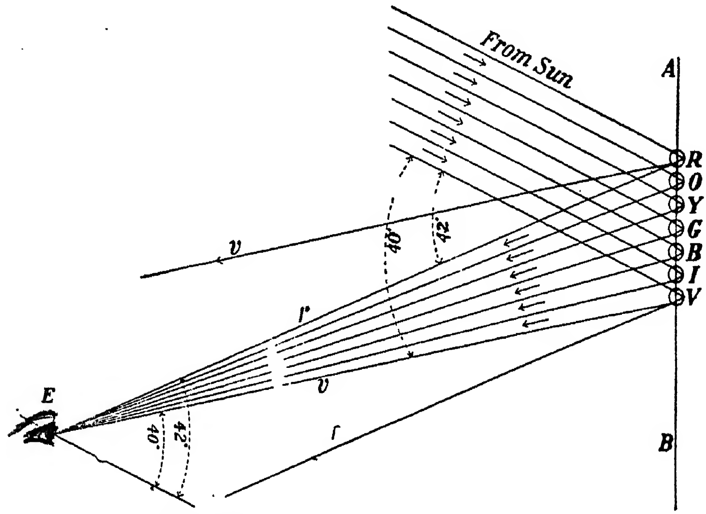


FIG. 498.—How the observer sees the different colours of the rainbow. Red comes from one drop, green from another, and so on.

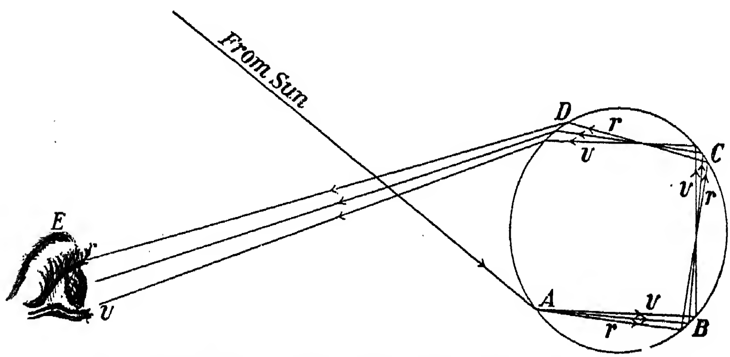
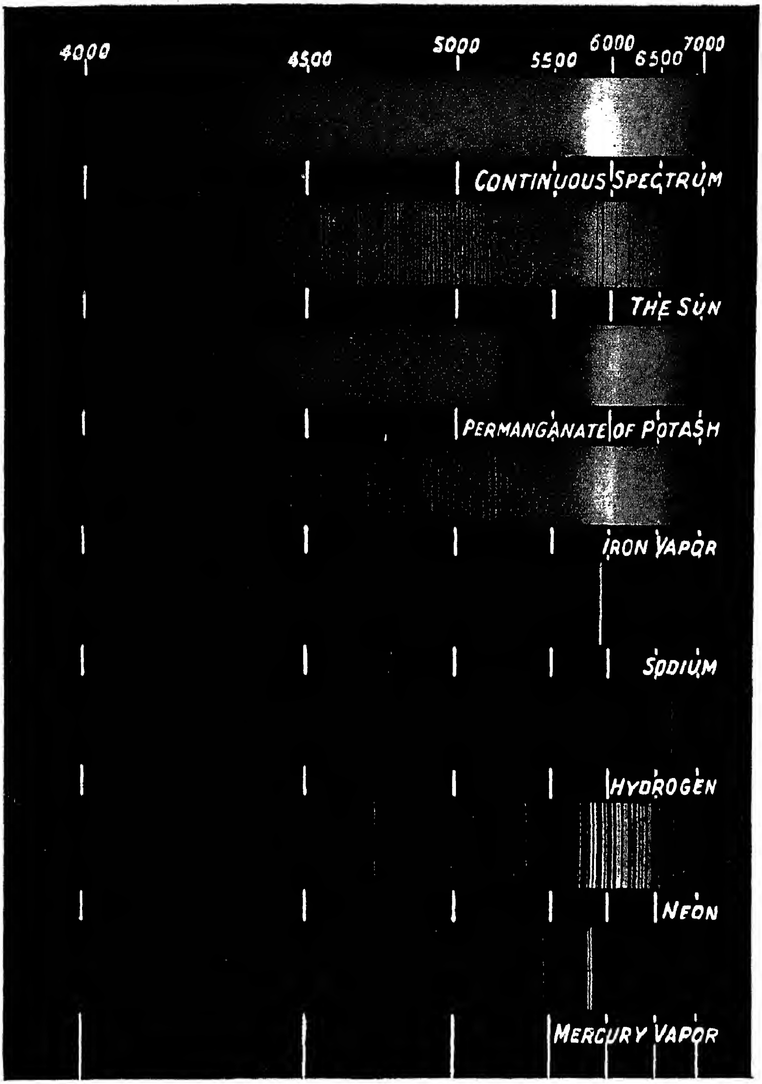


FIG. 499.—Showing how the light passes to form the secondary (outer) bow.

outside of the bow. In order to produce the secondary bow the light enters the drop at *A* (Fig. 499) is reflected at *B* and *C*, and is refracted out at *D*. The colours in the secondary bow are in the reverse order to those in the primary bow.



SPECTRA OF VARIOUS KINDS

The first is a continuous spectrum; in it are no lines, dark or bright. In the next two are dark lines or bands, due to the absorption of different wave lengths. The last five are spectra of gases or vapours made luminous by an electric current; they show only bright lines.

The numbers at the top give the wave lengths in angstroms.

Photographs by Elizabeth J. Allin. Prints from the negatives were coloured and then reproduced.

444. Achromatic Lenses. The focal length of a lens depends on the index of refraction of the material from which the lens is made; and as the index varies with the wavelength, or the colour, the focal length is not the same for all colours.

As the violet rays are refracted more than the red, the focal length for violet is shorter than for red. Thus, in Fig. 500, the violet rays come to a focus at V while the red converge to R, the foci for the other colours lying between V and R. A screen held at A will show a circular patch of light edged with red, while if at B, it will show a patch edged with violet. This inability to converge all the constituents of a beam of white light to a single point is a serious defect in single lenses, and is known as **chromatic aberration.**

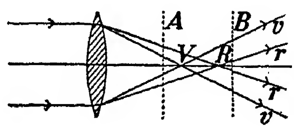


FIG. 500.—The foci for violet and red rays are quite separated.

Thus there is no single point to which all the light converges, and in determining the principal focus it is usual to find the focus for the yellow rays, which are the brightest.

Dollond, a London optician, discovered in 1757 a method of overcoming chromatic aberration. The arrangement is shown in Fig. 501. Flint-glass is more dispersive than crown-glass, and a crown-glass converging lens is combined with a flint-glass di-
of

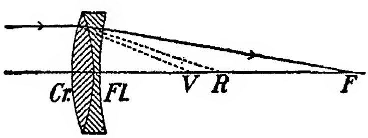


FIG. 501.—An achromatic combination of lenses.

The crown-glass lens would converge the red rays to R and the violet to V, while the flint-glass then diverges both of them so that they come together at F. Such compound lenses are said to be **achromatic,** which means "without colour." They are used in all telescopes and microscopes.

QUESTIONS AND PROBLEMS

1. Describe the three types of spectra and explain how they are produced. Give examples of each type.

2. Describe the solar spectrum and explain how, by means of it, we can determine what chemical elements are contained in the sun. Name some of these elements.

3. What sort of spectrum should be given by (*a*) light from the moon; (*b*) from a bright cloud?

4. Where would you look for a rainbow in the evening? At what time can one see the longest bow? Under what circumstances could one see the bow as a complete circle?

5. What is meant by *chromatic aberration?* Explain how a combination of two lenses can get rid of it.

6. An achromatic lens is composed of a converging lens of focal length 10 cm., and a diverging lens of focal length 15 cm. What is the focal length of the combination? (§ 429.)

7. On observing the spectrum of sodium vapour in a spectroscope two fine lines are seen close together. What will be the effect of widening the slit?

REFERENCES FOR FURTHER INFORMATION

Edser: *Light for Students*, Chapter 4.
Newall: *The Spectroscope and its Work* (Elementary and good).
Nightingale: *Heat, Light and Sound.*
Houstoun: *Light and Colour.*
Wright: *Light.*
W. H. Bragg: *The Universe of Light.*

CHAPTER LXV

OPTICAL INSTRUMENTS

445. Photographic Camera. A pin-hole camera was described in § 358 and a simple lens camera in § 422. The former can take good photographs but as the hole through which the light must pass is small the time of exposure is long. This serious defect is overcome by using a lens, but a simple lens as illustrated in Fig. 467 is not satisfactory. The image is not sharp in every part and it is fringed with colour; in other words, the lens is not achromatic (see § 444). Special lenses with several components must be employed, and they are now obtainable at reasonable prices.

In Fig. 502 is illustrated an ordinary camera. In the tube *A* is the lens, and at the other end of the apparatus is a frame *C* containing a piece of ground glass. By means of the bellows *B* this is moved back and forth until the scene to be photographed is sharply focussed on the ground glass. Then a holder containing a sensitive plate or film is inserted in the place of the frame *C*, the sensitized surface taking exactly the position previously occupied by the ground surface of the glass. The exposure is then made, that is, light is admitted through the lens to the sensitive plate, after which, in a dark room, the plate is removed from its holder, developed and fixed.

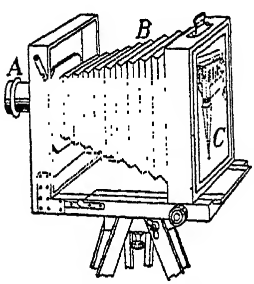


Fig. 502.—A photographic camera.

The production of camera lenses or objectives has been brought to a high degree of perfection in recent years. The aim sought is to secure a picture which is sharply focussed

all over the plate (or film) and to obtain it with a very short exposure. To ensure the former condition the component lenses of the objective must be made from glass of appropriate index of refraction and dispersive power and their surfaces must have the proper curvature; while for short exposures the diameter of the lens must be large relative to its focal length. A section of a successful lens is shown in Fig. 503, which, it will be seen, is a combination of four separate lenses. Others contain even more separate lenses, and as their manufacture demands much time and great skill, they are expensive. Great ingenuity has been expended in producing extremely compact and efficient cameras. The camera in Fig. 504 is $5\frac{1}{2} \times 3\frac{1}{2} \times 2$ in. in size and takes 36 photographs, each $1 \times 1\frac{1}{2}$ in. on a roll-film. The focal length f of the lens is 2 in. and lenses of different diameters may be used — $f/3\cdot6$, $f/2$, $f/1\cdot5$, etc., i.e., $0\cdot6$, $1\cdot0$, $1\cdot3$ in., respectively. The greater the diameter relative to the focal length the faster is the lens.

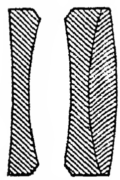


FIG. 503.—Section of a Zeiss "Tessar" photographic objective. The light enters in the direction shown by the arrow.

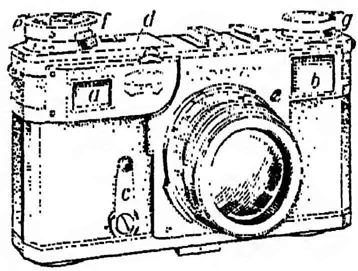


FIG. 504.—A modern miniature camera, *a*, *b* lenses of meter for focussing; *b*, also view finder; *c*, to delay shutter; *d*, focussing wheel; *e*, knob for winding shutter; *f*, button to release shutter; *g*, knob to re-wind film.

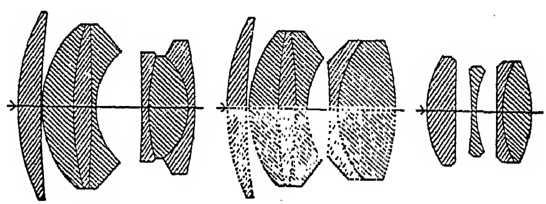


FIG. 505.—Sections of three fast camera lenses.

446. The Eye. The eye behaves much like a camera and is the most wonderful of all optical instruments. It is almost spherical in shape (Fig. 506). The horny outer covering, the "white of the eye," is called the **sclerotic** coat. The front portion of this protrudes like a watch face and is called the **cornea.** Within the sclerotic is the **choroid coat,** within this, again is, the **retina.**

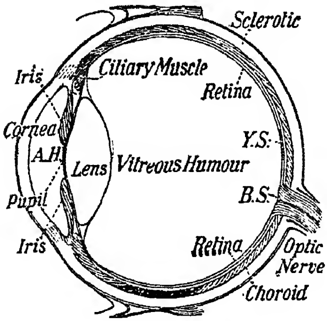


Fig. 506.—Horizontal section of a right eye. *A.H.*, aqueous humour; *Y.S.*, yellow spot; *B.S.*, blind spot.

The portion of the choroid coat visible through the cornea is called the **iris.** This forms an opaque circular diaphragm, which is variously coloured in different eyes. The aperture in it is called the **pupil,** and the size of the pupil alters involuntarily to suit the amount of light which enters the eye. When the light is feeble the pupil is large. On passing from darkness into a brilliantly lighted room the eye is at first dazzled, but the pupil soon contracts and keeps out the excessive supply of light.

Behind the pupil is the double-convex **crystalline lens.** By means of the muscles attached to the edge of the lens, the curvature of its faces, and hence its converging power, can be changed at will. The portion of the eye between the lens and the cornea is filled with a watery fluid called the **aqueous humour,** while between the lens and the retina is a transparent jelly-like substance called the **vitreous humour.** The **retina** is a semi-transparent net-work of nerve-fibres, formed by the spreading out of the termination of the optic nerve. It corresponds to the film in the camera.

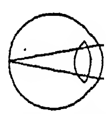


Fig. 507.—Normal eye receiving light from a distant object.

447. Defects of the Eyes. A person possessing normal vision can see distinctly objects at all distances varying from 8 or 10 inches

up to infinity. Light from all such is converged upon the retina (Fig. 507). But, as we well know, there are many eyes with defects, the chief of which are **short-sightedness, long-sightedness, and astigmatism.**

A short-sighted eye cannot see objects at any considerable ;e from The image of an object near at hand is produced on the retina, but the eye cannot accommodate itself for one farther off. In such a case the image is formed in front of the retina, (*a*, Fig. 508) and to the observer it appears blurred. In a short-sighted eye the lens is too strongly convergent, and in order to remedy this we must use spectacles producing the opposite effect, that is, having (*b*, Fig. 508).

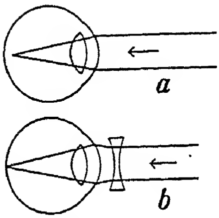


FIG. 508.—A short-sighted eye and its correction.

A long-sighted eye, in its passive condition, brings parallel rays of light to a focus behind the retina (*a*, Fig. 509). Such an eye can accommodate itself for distant objects, bringing the image forward to the retina; but for near objects its power of accommodation is not sufficient. In this case the crystalline lens is not converging enough, and in order to assist it spectacles with converging lenses should be used (*b*, Fig. 509). As a person grows older there is usually a loss of the power of accommodation, and the eye becomes long-sighted, requiring the use of converging spectacles.

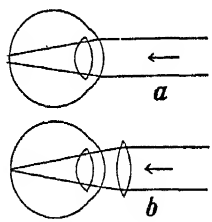


FIG. 509.—A long-sighted eye and its correction.

The defect known as astigmatism is due to a lack of symmetry in the surfaces of the cornea and the lens, but principally in the former. Ordinarily these are spherical, but sometimes the curvature is greater in one plane than in others. If a diagram, as shown in Fig. 510 be drawn about one foot in

diameter and viewed from a distance of about 15 feet, an astigmatic eye will see some of the radii distinctly, while those at right angles will be blurred. In most cases the vertical section of the cornea of an astigmatic eye is more curved than a horizontal section. The proper spectacles to use are those in which one surface of the lens is a part of a cylinder instead of a sphere.

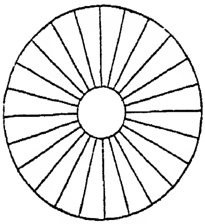


FIG. 510.—Diagram fo testing for astigmatism.

448. Compound Microscope. For magnifications higher than those obtainable with a single lens (§ 425) we must

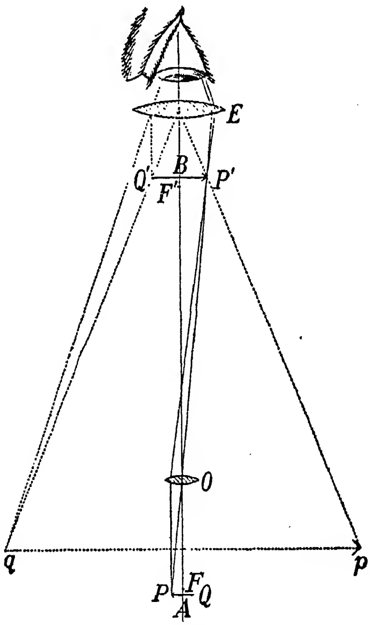


FIG. 511.—Diagram illustrating the compound microscope.

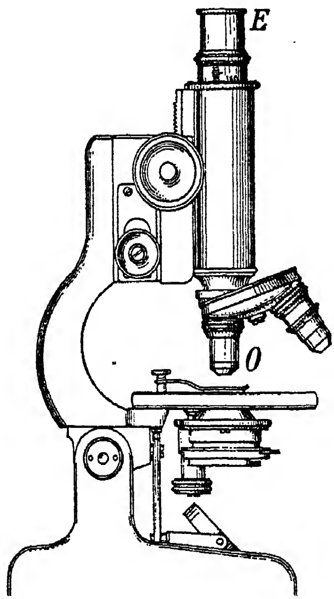


FIG. 512.—A compound microscope.

use a combination of convex lenses known as a compound microscope. In its simplest form it consists of two lenses, the objective and the eyepiece, the action of which is illustrated in Fig. 511.

The object PQ is placed at A, before the objective O and just beyond its principal focus. Thus a real enlarged inverted image $P'Q'$ is produced at B, and the eyepiece E is so placed that $P'Q'$ is just within its focal length. The eyepiece E then acts as a simple microscope magnifying $P'Q'$. It forms an enlarged virtual image pq at the distance of distinct vision from the eye. This distance is approximately the length of the microscope tube. A modern compound microscope is shown in Fig. 512.

449. Astronomical Telescope. The arrangement of the lenses in the ordinary astronomical telescope is the same in principle as in the compound microscope. In the case of the latter, however, the object to be observed is near at hand and we can place it near the objective. In these circumstances a lens of short focal length is best to use.

But the objects viewed by the telescope are far away, and we must use an objective with as great a focal length as possible. The reason for this will be evident from Fig. 513. Let AC be a ray from the upper part of the object looked at, passing through the centre C of the objective O.

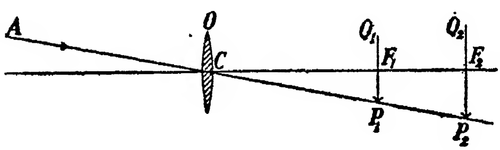


FIG. 513.—Showing why the objective of an astronomical telescope should have a long focus.

Now, the image of an object at a great distance is formed at the principal focus. If, then, F_1 is the principal focus, P_1Q_1 is the image; and if F_2 is the principal focus, P_2Q_2 is the image. It is clear that P_2Q_2 is greater than P_1Q_1, and indeed that the size varies directly as the focal length. Hence, the greater the focal length of the objective the larger will be the image produced by it.

Further, since the celestial bodies (except the sun) are very faint, the diameter of the objective should be large, in order to collect as much light from the body as possible.

A diagram illustrating the action of the telescope is given in Fig. 514. The objective forms the image at its principal focus B, that is, $OB = F$, its focal length. This is further magnified by the eyepiece E, which forms the image at pq.

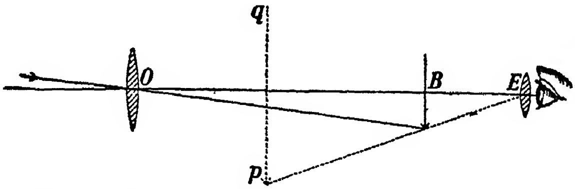


Fig. 514.—The principle of the astronomical telescope.

B is just within the principal focus of the eyepiece, and so OE, the distance between objective and eyepiece, is approximately equal to $F + f$, the sum of their focal lengths.

The magnification produced by the telescope is equal to F/f, though we cannot here deduce this formula.*

In the great telescope of the Lick Observatory the diameter of the objective is 36 inches and its focal length is 57 feet. If an eyepiece of focal length $\frac{1}{2}$-inch is used, the magnification is 1368. The diameter of the Yerkes telescope (belonging to the University of Chicago) is 40 inches and its focal length is 62 feet. This is the largest refracting, or lens, telescope in existence. (See plate 30, facing page 463). A longitudinal section of a small astronomical telescope is given in Fig. 515.

Fig. 515.—Section of a small astronomical telescope.

450. Reflecting Telescope. In another type of astronomical telescope a concave mirror is used instead of a lens. (In Fig. 414 it is shown how a concave mirror produces the image of an object.) The mirror is usually made by hollowing out a glass disc and then depositing on it, by a

*See Chant and Burton: *College Physics*, p. 519.

chemical process, a layer of silver. When this is polished, it forms the finest of reflecting surfaces. Very recently the method of evaporating aluminium and depositing it upon the surface of the glass has been introduced. It reflects the light well and is much more durable than silver.

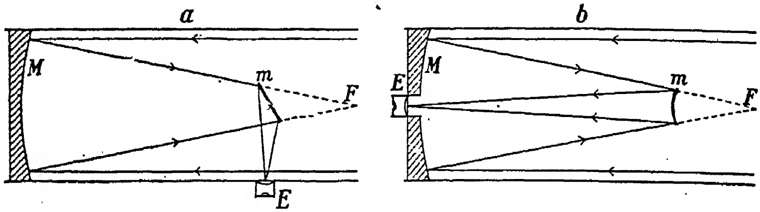


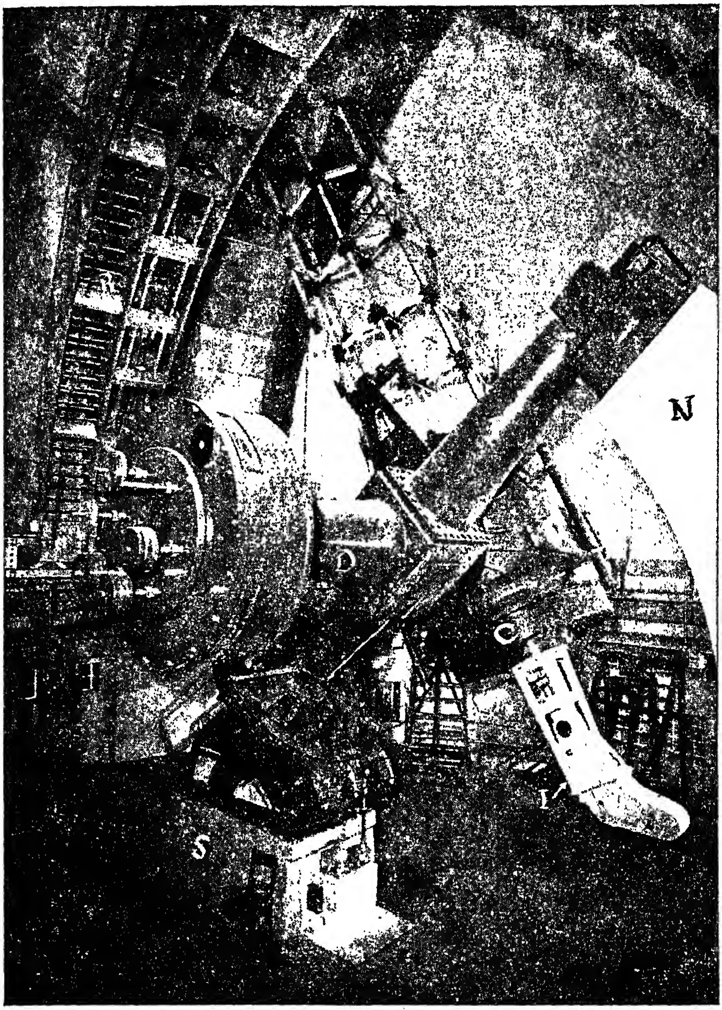
FIG. 516.—Two forms of the reflecting telescope.

In Fig. 516 is shown two methods by which the image produced by the mirror is observed. The light rays from the distant object pass up the tube and upon striking the mirror M are converged towards its principal focus F. Before arriving there, however, they meet (in Fig. 516a) a plane mirror m which reflects the light to the eyepiece E, into which the eye looks. In Fig. 516b a convex mirror reflects the light back through a hole in the mirror to the eyepiece E.

The earliest reflecting telescope was made with his own hands, by Sir Isaac Newton in 1668 and he employed the first form. The second form (Fig. 516b) was devised by Cassegrain and bears his name.

Some very large reflecting telescopes have been constructed. One of the largest is at Richmond Hill, Ont. (near Toronto), Plate 29. The mirror in it is 74 inches in diameter, (see Fig. 430) and the entire moving part of the telescope weighs over 50 tons.

451. Prism Binocular. The construction of the prism binocular is illustrated in Fig. 517, a portion of one side being cut away to reveal what is within. The arrangement of the lenses is optically similar to that in the astro-



THE GREAT REFLECTING TELESCOPE OF THE DAVID DUNLAP OBSERVATORY AT RICHMOND HILL, NEAR TORONTO

One end of the polar axis *P* rests on the north pier *N*, the other on the south pier *S*, and it is mounted exactly parallel to the axis of the earth. At the lower end of the tube *T* is the iron cell *C* containing the great

(Fig. 430) and to the the

the spectrum of T

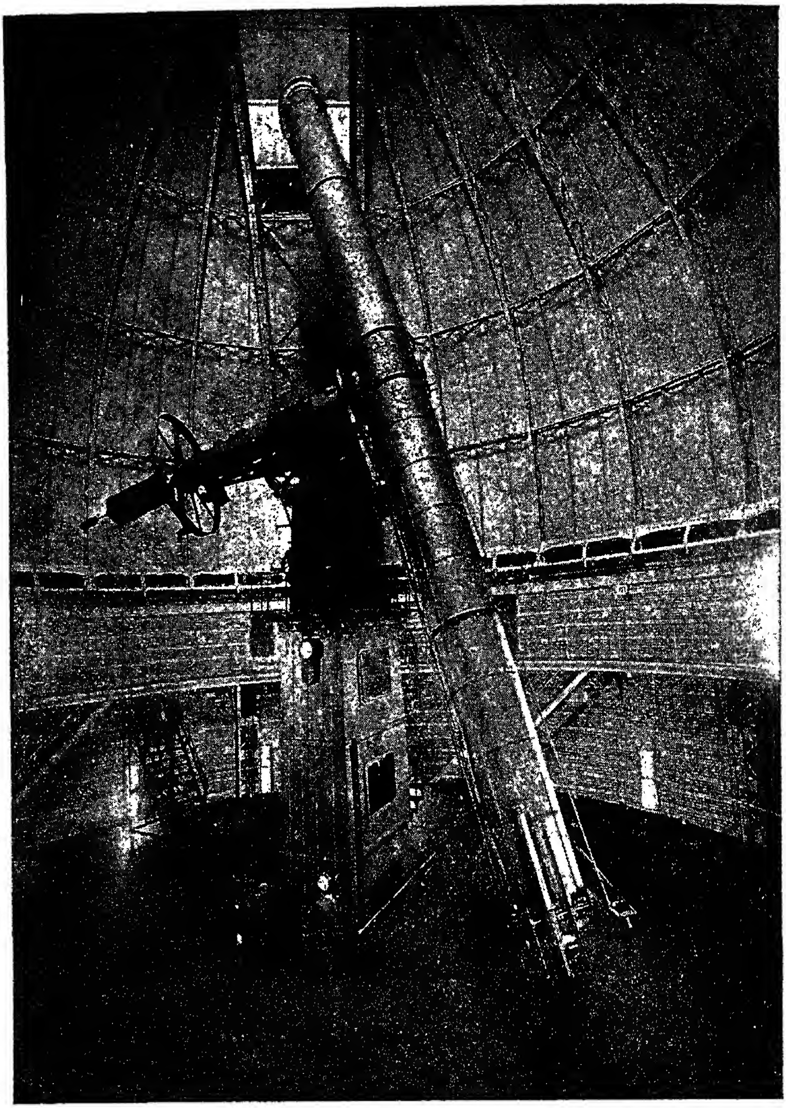
e declination axis which passes through *D*

which runs on rails at top and bottom, the

of the tube to work there. This telescope

ɔire. One slightly smaller is at Victoria, B.C.

(Photograph from the David Dunlap Observatory)



THE GREAT REFRACTING TELESCOPE OF THE YERKES OBSERVATORY
AT WILLIAMS BAY, WIS.

This is the largest lens-telescope in existence. The diameter of the lens is 40 inches and its focal length is 62 feet.

(Photograph from the Yerkes Observatory)

nomical telescope, but the light is reflected back and forth by two total-reflection prisms, which makes it necessary for the binocular tube to be only one-third the length of the telescope tube. The light enters the objective at *b*, passes through the two prisms as shown, and emerges from the eyepiece at *a*. In the astronomical telescope the image is inverted, which causes no inconvenience, but when terrestrial objects are being observed inversion is objectionable. In the prism binocular the two reflections erect the image. The diameter of the field of view is from 2 to 3 times that of the ordinary field-glass of the same power.

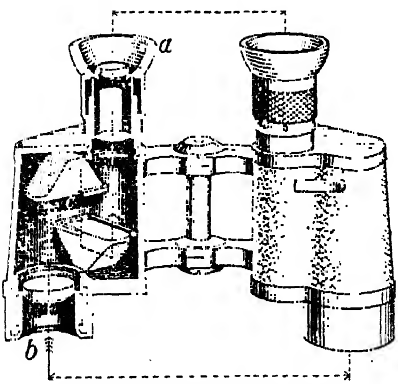


Fig. 517.—The prism binocular.

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Louis Bell: *The Telescope.*
Ingalls: *Amateur Telescope Making.*

PART VIII—ELECTRICITY AND MAGNETISM

CHAPTER LXVI

MAGNETS AND MAGNETIC SUBSTANCES

452. Natural Magnets. In various countries there is found an ore of iron which possesses the remarkable power of attracting small bits of iron. Specimens of this ore are known as **natural magnets.** This name is derived from Magnesia, a town of Lydia, Asia Minor, in the vicinity of which the ore is supposed to have been abundant. Its modern name is magnetite. It is composed of iron and oxygen, the chemical formula for it being Fe_3O_4.

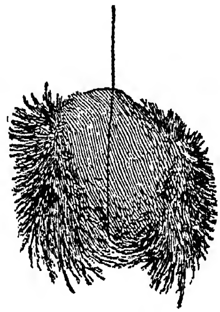


FIG. 518.—Iron filings clinging to a natural magnet.

If dipped in iron filings, many will cling to it, and if it is suspended by an untwisted fibre, it will come to rest in a definite position, thus indicating a certain direction. On account of this it is known also as a **lodestone,** (*i.e.*, leading-stone) (Fig. 518.)

FIG. 519.
A bar-magnet.

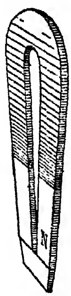


FIG. 520.
A horse-shoe magnet with keeper.

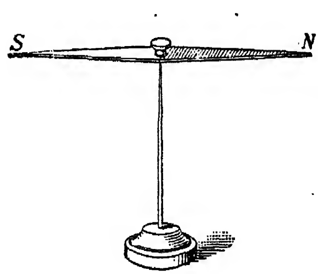


FIG. 521.
A compass-needle magnet.

453. Artificial Magnets. If a piece of steel is stroked over a natural magnet, it becomes itself a magnet. There are,

however, other and more convenient methods of magnetizing pieces of steel which will be explained later (see § 546), and as steel magnets are much more powerful and more convenient to handle than natural ones, they are always used in experimental work.

Permanent steel magnets are usually of the bar, the horseshoe or the compass-needle shape, as illustrated in Figs. 519, 520, 521.

454. Poles of a Magnet. Iron filings when scattered over a bar-magnet are seen to adhere to it in tufts near the ends, none, or scarcely any, being found at the middle (Fig. 522).

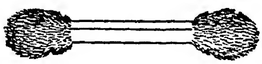


Fig. 522.—The filings cling mostly at the poles.

The strength of the magnet seems to be concentrated in certain places near the ends; these places are called the poles of the magnet, and a straight line joining them is called the **axis of the magnet.** If the magnet is suspended so that it can turn freely in a horizontal plane (Fig. 521), this axis will assume a definite north-and-south direction, in what is known as the **magnetic meridian,** which is usually not far from the geographical meridian. That end of the magnet which points north is called the **north-seeking** pole, or simply the *N*-pole, the other the **south-seeking** pole, or *S*-pole.

455. Magnetic Attraction and Repulsion. Let us bring the *S*-pole of a bar-magnet near to the *N*-pole of a compass-needle (Fig. 523). There is an attraction between them. Next present the same pole to the *S*-pole of the needle; it is repelled. Now reverse the ends of the magnet; we find that its *N*-pole attracts the *S*-pole of the needle but repels the *N*-pole.

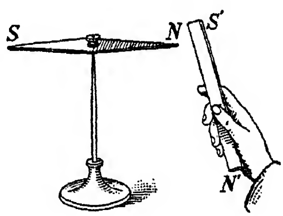


Fig. 523.—The *S*-pole of one magnet attracts the *N*-pole of another.

We thus obtain the law: **Like magnetic poles repel, unlike attract each other.**

This experiment can be repeated with very simple means. Magnetize two sewing-needles by rubbing them, always in the same direction, against one pole of a magnet. Then thrust them into corks floating on the surface of water and push one over near the other; the attractions and repulsions will be beautifully shown.

It is to be observed that unmagnetized iron or steel will be attracted by *both* ends of a magnet. It is only when both bodies are magnetized that we can obtain repulsion.

456. Induced Magnetism. Hold a piece of iron rod, or a nail,* near to, but not touching, one pole of a strong magnet; it becomes itself a magnet, as is seen by its power to attract iron filings or small tacks placed near its lower end (Fig. 524). The nail is said to be magnetized by induction, *i.e.*, by 'introduction.' Allow the nail to touch the pole of the magnet; it will be held there. A second nail may be suspended from the lower end of this one, a third from the second, and so on (Fig. 525). Now remove the magnet; the chain of nails falls to pieces.

Fig. 524.—A nail if held near a magnet becomes itself a by induction.

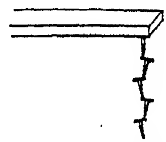


Fig. 525.—A chain of magnets by induction.

We thus see that a piece of iron becomes a **temporary** magnet when it is brought near one pole of a permanent steel magnet. Its polarity can be tested in the following way:

Suspend a bit of soft-iron (a narrow strip of tinned-iron is very suitable), and place the *N*-pole of a bar-magnet near it (Fig. 526). Then bring the *N*-pole of a second bar-magnet near the end *n* of the strip, farthest from the first magnet. The end *n* is repelled, showing that it is an N-pole. Next, bring the *S*-pole of the second magnet slowly towards the end *s* of the strip. Repulsion is again observed.

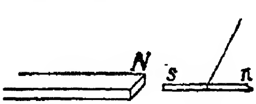


Fig. 526.—Polarity of induced magnestism.

*Ordinary steel nails are not very satisfactory. Use clout nails or short pieces of stove-pipe wire.

This shows, as we should expect from the law of magnetic attraction and repulsion (§ 455), that the induced pole is opposite in kind to that of the permanent magnet adjacent to it.

457. Retentive Power. The bits of iron in Figs. 524-6, retain their magnetism only when they are near the magnet; when it is removed, their polarity disappears.

If hard-steel is used instead of soft-iron, the steel also becomes magnetized, but not so strongly as the iron. However, if the magnet is removed the steel will still retain some of its magnetism. It has become a **permanent** magnet.

Thus steel offers great resistance both to being made a magnet and to losing its magnetism. It is said to have great **retentive power.**

On the other hand, soft-iron has small retentive power. When placed near a magnet it becomes a stronger magnet than a piece of steel would, but it parts with its magnetism quite as easily as it gets it.

458. Magnetic Substances. Besides steel and iron, nickel and cobalt are the only elementary substances which exhibit magnetic effects in any notable degree.

In recent years, however many special alloys have been developed which show remarkable magnetic properties. Permalloy, a 4-to-1 alloy of nickel and iron, is very easily magnetized. Another alloy of steel, cobalt and chromium, known as cobaltchrom, has high retentive power and consequently is suitable for permanent magnets. The name alnico has been given to an alloy consisting of aluminium 6 to 15 per cent., nickel 12 to 30 per cent., cobalt 10 per cent. or less, and the remainder iron. It is specially suitable for permanent magnets. The material is too hard to be machined and must be cast and then ground to shape. In Fig. 527 is shown a small alnico horse-shoe magnet which

weighed 22 gm. but lifted over 1200 gm. Somewhat similar alloys have been developed in Japan and England. On the other hand steel alloyed with 13 per cent. manganese is almost non-magnetic.

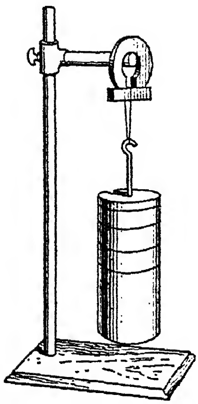


Fig. 527.—A small horse-shoe magnet made from alnico. It weighed 22 gm. and lifted over 1200 gm.

Heusler, a German physicist, discovered a strange series of alloys with marked magnetic properties. They are composed of manganese about 25 per cent., aluminium (from 3 to 15 per cent.) and copper. These substances taken singly are non-magnetic but when alloyed together are strongly magnetic.

As in many other properties of matter, there is a great mystery in the behaviour of these substances.

CHAPTER LXVII

LINES OF FORCE AND MAGNETIC SHIELDING

459. Field of Force about a Magnet. The space about a magnet, in any part of which the force from the magnet can be detected, is called its **magnetic field.** The field can be explored by means of a small compass-needle, as follows:

Experiments. 1. Place a bar-magnet on a sheet of paper and slowly move a small compass-needle about it. The action of the two poles of the magnet on the poles of the needle will cause the latter to set itself at various points along lines which indicate the direction of the force from the magnet. These curves run from one pole to the other. In Fig. 528 is shown the direction of the needle at several points, as well as a line of force extending from one pole to the other.

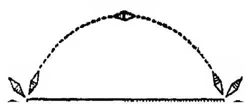


FIG. 528.—Position assumed by a needle near a bar-magnet.

2. Another simple and effective way to map the field is by means of iron filings. Place a sheet of paper over the magnet, and sift from a muslin bag iron filings evenly and thinly over it. Tap the paper gently. Each little bit of iron becomes a magnet by induction, and tapping the paper assists them to arrange themselves along the magnetic lines of force. Fig. 529 exhibits the field about a bar magnet, while Fig. 530 shows it about similar poles of two bar-magnets placed near together.

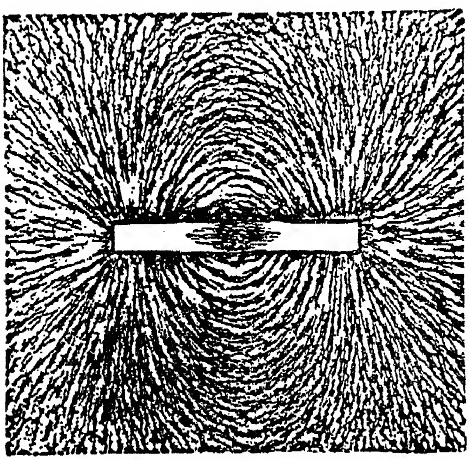


FIG. 529.—Field of force of a bar-magnet.

The magnetic force, as we have seen, is greatest in the

neighbourhood of the poles, and here the curves shown by the filings are closest together. Thus the direction of the curves indicates the direction of the lines of force, and their closeness together at any point indicates the strength of the magnetic force there.

There are several ways of making these filings figures permanent. Some photographic process gives the best results, but one may use paper which has been dipped in melted paraffin. If the paper is heated the filings sink into the wax and are held firmly in it when it cools.

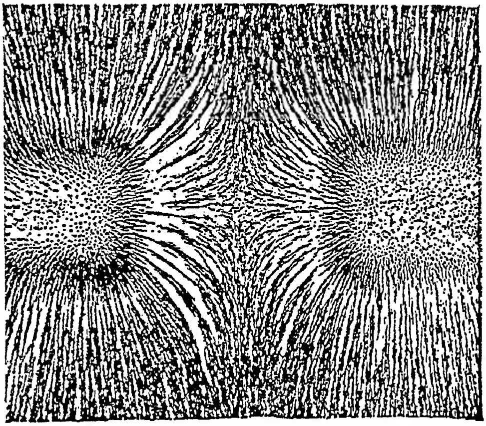
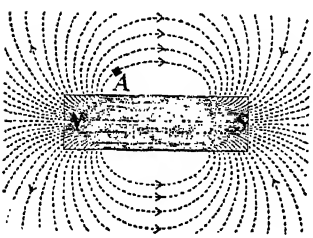


FIG. 530.—Field of force of two like poles.

460. Properties of Lines of Force. The lines of force belonging to a magnet are considered to begin at the N-pole, pass through the surrounding space, enter at the S-pole and then continue through the magnet to the N-pole again (Fig. 531). Thus each line of force is a closed curve. It is evident, also, that if we could detach an N-pole from a magnet and place it on any line of force, at A for instance, it would move along that line of force until it would come to the S-pole.



rounding medium to the
then through the magnet
starting point.

Experiment. To illustrate this motion arrange apparatus as in Fig. 532. A bar-magnet A is placed on the bottom of the glass vessel B, which is filled with water to a depth of about 8 inches. A magnet

D (a magnetized knitting-needle will serve) is pushed through a cork C, which supports it in the water with its N-pole near the magnet A. When the floating magnet is placed with its lower end near the N-pole of A, it will move in a curved path until it stands over the S-pole of A. The upper pole of D is much farther from the stationary magnet than the lower pole and, consequently, the movement is practically the same as that of a detached or free N-pole.

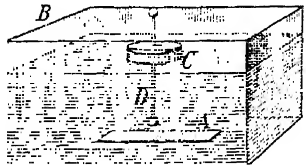


FIG. 532.—Illustrating motion along a line of force.

Great use is made of the conception of lines of force in computations in magnetism and electricity, for example, in designing dynamos. This method of dealing with the subject was introduced by Faraday about 1830.

461. Magnetic Shielding. Most substances when placed in a magnetic field make no appreciable change in the lines of force, but there is one very pronounced exception to this, namely, iron.

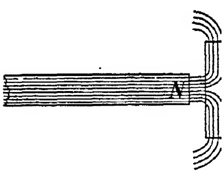


FIG. 533.—Lines of force pass through iron more easily than through air.

If a bar of iron is placed near the N-pole of a bar-magnet, the resulting field of force will be as shown in Fig. 533. The lines of force tend to crowd together in the iron as if they experienced less resistance to passing through it than through air. Very few lines pass through the iron into the region AB, practically all being deflected so that they follow the iron as far as possible before passing out into the air. This behaviour of iron has been applied to the problem of shielding from magnetism, as can be illustrated in the following way:

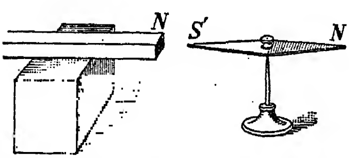


FIG. 534.—Arrangement for testing magnetic shielding.

Experiment. Place a bar-magnet with one pole about 10 cm. from a large compass-needle (Fig. 534). Pull aside the needle and let it go. It will continue vibrating for some time. Count the number of vibra-

tions per minute. Then push the magnet up until it is 6 cm. from the needle, and again time the vibrations. They will be found to be much faster. Next, put the magnet 3 cm. from the needle; the vibrations will be still more rapid. Thus, the stronger the force of the magnet on the needle, the faster are the vibrations.

Now, while the magnet is 3 cm. from the needle, place between them a board, a sheet of glass or of brass, and determine the period of the needle. No change will be observed. Next, insert a plate of iron. The vibrations will be much slower, thus showing that the iron has shielded the needle from the force of the magnet.

The lines of force on entering the iron are deflected as shown in Fig. 535, so that very few pass through to the compass-needle. The brass

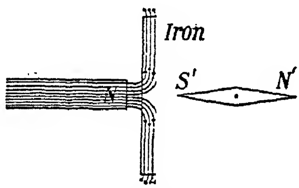


FIG. 535.—The lines of force crowd into the iron plate.

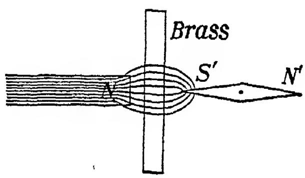


FIG. 536.—The lines of force pass freely through the brass plate.

sheet produces no such effect (Fig. 536) and the field of force is unaltered by its presence.

462. Magnetic Permeability. When a magnetic substance is placed in a magnetic field, magnetism is induced in the substance, and as a consequence there are more lines of magnetic force entering and leaving the substance than there would be entering and leaving the very space occupied by it if the space was a vacuum. The ratio of the number of lines of magnetic force entering and leaving the substance to the number there would be if the substance were replaced by a vacuum is called the **magnetic permeability** of the substance.

For soft-iron this ratio may be as high as 3000 to 4000, while for hard-steel it is about 200. This explains why soft-iron becomes a stronger magnet by induction than hard-steel.

The value of the permeability for any given sample is not constant but it decreases rapidly as the induced magnetism approaches the saturation value.

463. Theory of Magnetism. Let us magnetize a knitting needle or a piece of clock-spring (Fig. 537); it exhibits a pole at each end, but no magnetic effects at the centre. Now score it with a file and break it at the middle. Each part is a magnet. If we break these portions in two, each fragment is again a magnet. Continuing this, we find that each free end always gives us a magnetic pole. If all the parts are closely joined again, the adjacent poles neutralize each other and we have only the poles at the ends, as before.

FIG. 537.—Each portion of a magnet is a magnet.

If a magnet is ground to powder, each fragment still acts as a little magnet and shows polarity.

Again, if a small tube filled with iron filings is stroked from end to end with a magnet, it will be found to possess polarity, which, however, will disappear if the filings are shaken up.

All these facts lead us to believe that a magnetic substance is composed of an infinite number of elementary magnets. We cannot say that they are the molecules of the substance although they are comparable in size. These ultimate magnetic particles will be designated **elementary magnets.** In an unmagnetized iron bar they are arranged in an irregular, haphazard fashion (Fig. 538), and so there is no combined action.

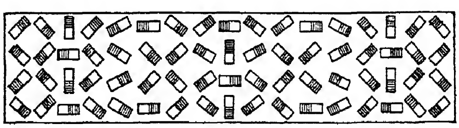


FIG. 538.—Usual haphazard arrangement of the elementary magnets of iron.

When the iron is magnetized the elementary magnets turn in a definite direction. Striking the rod while it is being

magnetized assists them to take up their new positions. On the other hand, rough usage destroys their alignment. When the magnet is made as strong as it can be, the elementary magnets are *all* arranged in regular order, as illustrated in Fig. 539. In this condition the magnet is said to be **saturated.**

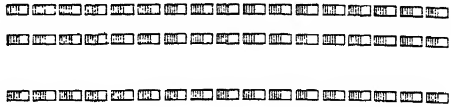


Fig. 539.—Arrangement of the elementary magnets when the iron is magnetized to saturation.

464. Magnetizing a Steel Bar. The above theory of magnetism explains what happens when a bar of steel is magnetized by rubbing it with another magnet.

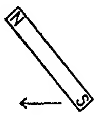


Fig. 540.—Magnetizing the steel bar *AB*.

If the steel bar *AB* (Fig. 540) is stroked in the direction of the arrow with the *S*-pole of a magnet *NS*, the elementary magnets in the bar will act like little compass-needles and will tend to turn so that their *N*-poles point towards *S* as it passes over them. Consequently, at the end of one stroke some of them will have turned so that their *N*-poles point towards *A* and their *S*-poles point towards *B*. Each succeeding stroke, if made in the direction of the arrow, turns more and more of the elementary magnets out of their haphazard positions and increases the strength of the new magnet. No magnetic effects are exhibited at the centre of the bar because the *N*-pole of each elementary magnet has the *S*-pole of another elementary magnet close to it, neutralizing its action. At the end *A*, however, we have an un-neutralized layer of *N*-poles and at the end *B* a similar layer of *S*-poles, with the result that the magnetism appears to be concentrated in these regions.

It is evident, then, that in magnetizing a bar the stroking should be done in only one direction, unless the magnet is

reversed at each stroke; also, if an S-pole is used for stroking, the end of the bar which it touches last becomes an N-pole and the reverse if an N-pole is used for stroking.

465. Demagnetization; Effect of Heat. After a piece of iron or steel has been magnetized, a demagnetizing action is called into existence by the reaction between the poles of the magnet and the elementary magnets which compose the magnet. If these elementary magnets move from their positions easily, as in soft iron, the regular arrangement of the elementary magnets is destroyed by this reaction as soon as the magnetizing agent is removed. In the case of steel the forces holding the elementary magnets in position are greater than for soft-iron. Consequently it is harder to magnetize steel, but after it has been magnetized it retains a large part of the magnetism which was induced into it.

Long magnets retain their magnetism more effectively than short ones and the placing of a keeper of soft-iron on a magnet (see Fig. 520), nullifies the action of the free poles and thereby diminishes their demagnetizing action on the elementary magnets.

A magnet loses its magnetism when raised to a bright red heat, and when iron is heated sufficiently, it ceases to be attracted by a magnet. This can be neatly illustrated in the following way. Heat a cast-iron ball, to a white heat if possible, and suspend it at a little distance from a magnet. At first, it is not attracted at all, but on cooling to a bright red it will be suddenly drawn in to the magnet.

The Heusler alloys, mentioned in § 458, behave peculiarly in respect to temperature. Above a certain temperature they are entirely non-magnetic. The temperature depends upon the proportions of aluminium and manganese present.

QUESTIONS AND PROBLEMS

1. What evidence have we that it is impossible to obtain a free magnetic pole?

2. A test-tube is filled with iron filings and the N-pole of a bar magnet is drawn from the open to the closed end several times. What change in the filings will be produced? What will be the effect of presenting the closed end of the tube to the S-pole of a compass-needle?

3. How could you magnetize a piece of steel so as to make it have an N-pole at *each* end?

4. You suspect that an iron rod is magnetized. How would you test this by means of a compass-needle?

5. Six magnetized sewing needles are thrust through six pieces of cork and are made to float near together in water with their N-poles upward. What will be the effect of holding (1) the S-pole, (2) the N-pole of a magnet above them? Try the experiment.

6. Arrange three similar bar magnets so that there will be the least possible magnetic effect on a neighbouring compass-needle.

7. Two similar bar magnets are set on end a few inches apart and a small magnetic needle is carried around the upper poles in a figure-of-eight course. How will it point in the various positions occupied (1) when the upper poles are like poles, (2) when they are unlike poles? Mark the positions on two diagrams.

8. Two precisely similar bar magnets are placed so as to form a +. Draw the field of force. Verify by performing the experiment with iron filings.

9. In dynamos and some other electrical machines it is necessary to have some parts which can be easily magnetized and which will lose their magnetism quickly when the magnetizing force is removed. What substance should be used?

10. The N-pole of a bar magnet is brought close to a point on the circumference of an iron ring. Make a sketch of the field of force about the magnet and the ring. Describe how a compass would act if placed inside the ring. Try the experiment.

11. Why is a permanent magnet injured when it is dropped or hammered?

12. If a piece of iron is heated hot enough, it loses any magnetism it may have, and if cooled when in a magnetic field, it becomes magnetized again. From our accepted theory of elementary magnets and their motions explain these effects.

CHAPTER LXVIII

THE EARTH'S MAGNETISM

466. The Earth a Magnet. The fact that the compass-needle assumes a definite position suggests that the earth or some other celestial body exerts a magnetic action. William Gilbert,* in his great work entitled *De Magnete*, which was published in 1600, demonstrated that our earth itself is a great magnet.

In order to illustrate his views Gilbert had some lodestones cut to the shape of spheres; and he found that small magnets turned towards the poles of these models just as compass-needles behave on the earth.

The magnetic poles of the earth, however, do not coincide with the geographical poles. The north magnetic pole was found by Sir James Ross† on June 1, 1831, on the west side of Boothia Felix, in N. Lat. 70° 5′, W. Long. 96° 46′. In 1904-5 Roald Amundsen, a Norwegian, explored all about the pole. Its present position is about N. Lat. 70°, W. Long. 97°, not far from its earlier position.

The south magnetic pole was only recently attained. On January 16, 1909, three members of the expedition led by Sir Ernest Shackleton discovered it in S. Lat. 72° 25′, E. Long. 155° 16′. In both cases the magnetic pole is over 1100 miles from the geographical pole, and a straight line joining the two magnetic poles passes about 750 miles from the centre of the earth.

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*Gilbert (1540-1603) was physician to Queen Elizabeth, and was England's first great experimental scientist.

†The cost of the arctic expedition, which was made by John Ross and his nephew James, was defrayed by a wealthy Englishman named Felix Booth.

467. Magnetic Declination. We are in the habit of saying that the needle points north and south, but it has long been known that this is only approximately so. Indeed, knowing that the magnetic poles are far from the geographical poles, we should not expect the needle (except in particular places) to point to the true north. In addition, deposits of iron ore and other causes produce local variations in the needle. The angle which the axis of the needle makes with the true north-and-south line is called the **magnetic declination.**

468. Lines of Equal Declination or Isogonic Lines. Lines upon the earth's surface through places having the same declination are called **isogonic** lines; that one along which the declination is zero is called the **agonic*** line. Along this line the needle points exactly north and south.

In the following table are given the values of the declination at several places in Canada and also at London, Eng., on January 1, 1910, January 1, 1923, and January 1, 1937.†

MAGNETIC DECLINATION

Place	Jan. 1, 1910	Jan. 1, 1923	Jan. 1, 1937
Halifax	21° 29′ W.	22° 15′ W.	22° 51′ W.
Montreal	15° 19′ W.	16° 11′ W.	16° 54′ W.
Toronto	5° 31′ W.	6° 28′ W.	7° 6′ W.
Winnipeg	13° 57′ E.	12° 59′ E.	11° 42′ E.
Edmonton	27° 24′ E.	26° 50′ E.	25° 33′ E.
Victoria	24° 34′ E.	24° 39′ E.	24° 12′ E.
Fort Norman	42° 6′ E.	41° 46′ E.	40° 22′ E.
London, England	15° 40′ W.	13° 45′ W.	11° 9′ W.

It will be seen that the declination at any point is subject to a slow change. At London in 1580 the declination was

*Greek, *isos* = equal, *gonia* = angle; *a* = not, *gonia* = angle.
†Supplied by the Dominion Observatory, Ottawa.

11° 17′ E. This slowly decreased, until in 1657 it was 0° 0′. After this it became west and increased until in 1816 it was 24° 30′; since then it has steadily decreased.

In Fig. 541 is a map showing the isogonic lines for the United States and Canada at the present time. It is of the utmost importance for navigators and explorers to be supplied with maps or tables giving the lines of equal magnetic declination. Aviators at the poles have peculiar difficulty with their compasses.

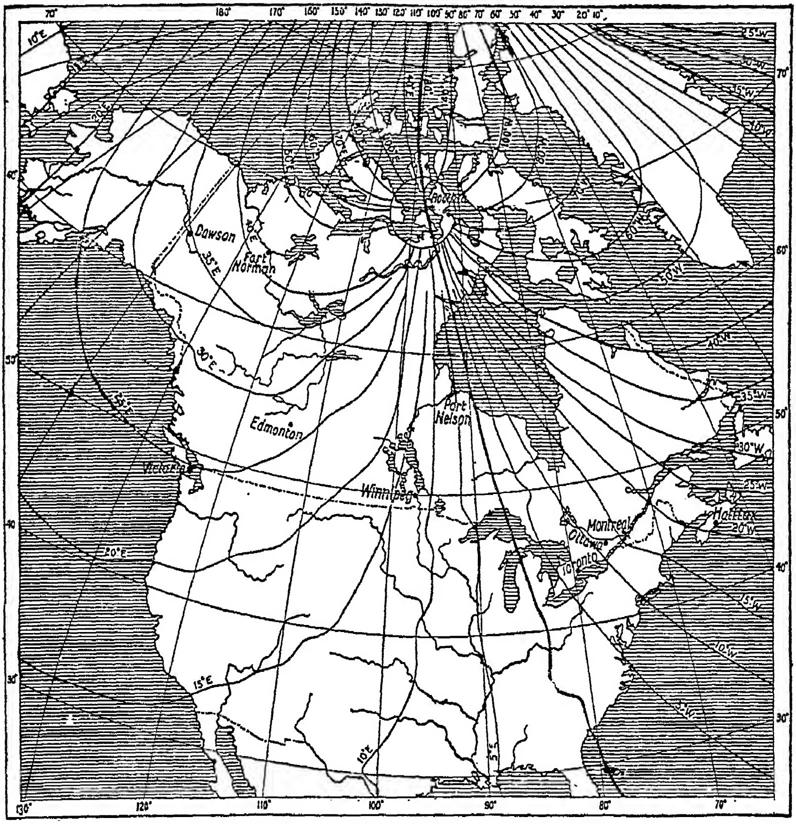


FIG. 541.—Isogonic Lines for Canada and the United States.

Note that at the St. of Belle Isle the compass points 35° west of true north, at Dawson 35° east, while near Port Arthur and Fort William on Lake Superior it points true north.

469. Magnetic Inclination or Dip. Fig. 542 shows an instrument in which the magnetized needle can move in a vertical plane. The needle before being magnetized is so adjusted that it will rest in any position in which it is placed, but when magnetized, the *N*-pole (in the northern hemisphere) dips down, making a considerable angle with the horizon. If the magnetization of the needle is reversed, the other end dips down. Such an instrument is called a **dipping needle.** When in use the axis of rotation should point east and west (*i.e.*, at right angles to the *magnetic* meridian), and the needle should move with the least possible friction.

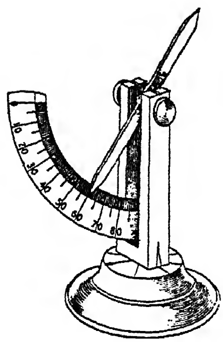


FIG. 542.—A simple dipping needle.

The angle which the needle makes with the horizon is called the **inclination** or **dip.** At the *magnetic* equator the dip is zero (or the needle is horizontal), but north or south of that line the dip increases, until at the magnetic poles it is 90°. Indeed, the location of the poles was determined by the dipping needle. The value of the dip, Jan. 1, 1937, is:

At Toronto, 74° 49′; Washington, 71° 20′; Mexico City, 47° 17′.

470. Earth's Magnetic Field. As the earth is a great magnet, it must have a magnetic field about it, and a piece of iron in that field should become a magnet by induction. If an iron rod (*e.g.*, a poker, or the rod of a retort stand) is held nearly vertical, with the lower end inclined towards the north, it will be approximately parallel to the lines of force and it will become magnetized. If struck smartly when in this position, its magnetism will be strengthened. (Why?) Its magnetism can be tested with a compass-needle. Carefully move the lower end towards the *S*-pole; it is attracted. Move it near the *N*-pole; it is repelled. This shows the rod to be a magnet.

Now, when a magnet is produced by induction, its polarity is opposite to that of the inducing magnet. Hence we see that what we call the north magnetic pole of the earth is opposite in kind to the N-pole of a compass-needle.

Iron posts in buildings and the iron in a ship when it is being built become magnetized by the earth's field.

471. Mariner's Compass. In the modern ship's compass several magnetized needles are placed side by side, such a compound needle having been found more reliable than a single one. The card, divided into 32 "points of the compass," is attached to the needle, the whole being delicately poised on a sharp iridium point fixed in a bowl which is supported on gimbal rings in order that the card may remain horizontal in spite of the rolling of the vessel. (Fig. 543.)

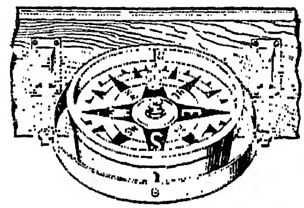


FIG. 543. — Mariner's Compass, mounted so as to remain horizontal always.

In some compasses the card is immersed in a liquid. This reduces the weight on the point and brings the needle to rest more quickly.

In order to steer in any particular direction, say north-west, the ship is turned until N.W. on the card is opposite a fixed vertical line a on the inside of the bowl. When the compass is installed, this "lubber's point" must be adjusted so that a line joining it to the iridium point is parallel to the keel of the ship.

In laying out a course on which to steer one must make due allowance for magnetic declination. If the true bearing* of a port is ten degrees (N. 10° E.) and the declination 6° W., the ship must be laid on a course sixteen degrees east of north, as indicated by the compass, in order that it may reach the port.

When a compass is being mounted in an iron ship masses of soft iron and also permanent magnets are arranged about it in such a way as to counteract the magnetic influence of the ship itself.

A magnetic compass on an iron ship must be continually checked as it is liable to disturbance from the ship itself or its cargo. In a submarine

*The *true bearing* of a line is the angle the line makes with the true north line. The *magnetic bearing* of a line is the angle the line makes with the magnetic north line. In each case the angle is measured in a clockwise direction from the north line.

vessel the magnetic compass cannot be used at all as the iron shell of the ship shields the compass from the earth's magnetic lines of force. Especially for such vessels the gyro-compass has been developed. In it the true north is indicated directly by means of a finely-constructed heavy wheel which rotates at very high speed—more than 8,000 times per minute. The gyro-compass has been so successful that it has now replaced the magnetic compass on many large commercial vessels.

QUESTIONS AND PROBLEMS

1. The same end of an iron bar is brought slowly up to the ends of a compass needle, one after the other, and attracts both of them. Is the bar magnetized? Explain what would happen if it were magnetized.

2. An iron pillar in a building is found to be slightly magnetized. Why should one expect it to be? Which end will be the N-pole? How would you test for polarity?

3. In France the end of the compass-needle pointing north is called the *Southern* pole and the end pointing south the *Northern* pole. Account for this.

4. How would you proceed to find, experimentally, the magnetic declination in the locality of your school? Would it be better to perform the experiment in a room or in the open? Give reasons for your answer.

5. Give two methods by which the true north-and-south line can be determined at any place.

6. The true bearing of Oswego from Toronto as obtained from a map is 94°. If the average declination on Lake Ontario is 6° W., on what compass bearing would a ship have to sail in proceeding (*a*) from Toronto to Oswego, (*b*) from Oswego to Toronto? (Use a good map of Ontario.)

7. The declination on Lake Ontario is changing at the rate of 3′ per annum. A ship leaves the Welland Canal for Kingston at 10 p.m., sailing by compass and allowing for a declination which was correct ten years ago. How far will the ship be off her course after a run of 100 miles? (One minute of angle is approximately equivalent to 1 inch per 100 yds.)

8. Criticise, from a scientific standpoint, the following lines in an old song:

> True as the needle to the pole
> Or as the dial to the sun.
>
> —*Barton Booth, 1681-1733*

REFERENCES FOR FURTHER INFORMATION

Reynolds: *Electricity and Magnetism*, Chapters 3 to 7.
Saunders: *A Survey of Physics*, Chapter 19.

CHAPTER LXIX

ELECTRICAL ATTRACTION AND REPULSION; THE ELECTRON THEORY

472. Introduction. Electrical appliances are very common now-a-days. In our homes we have electric lamps, stoves, toasters, irons, vacuum cleaners, washers and other labour-saving devices,—and we must not forget the radio. In our factories electric motors drive the machinery, and in our automobiles electricity cranks the engine, ignites the gasoline-air mixture in the cylinders and operates the car lights. Most impressive of all, we have world-encircling systems of communication by means of the telephone, telegraph and radio. These wonderful applications of electricity have been devised and perfected largely within the last fifty years and they have completely changed our manner of living.

473. Electrical Attraction. Although the achievements mentioned in the preceding paragraph are so recent our earliest knowledge of electricity dates as far back as 600 B.C. Thales, a famous physicist and astronomer who lived in Miletus at the mouth of the Maeander river in Asia Minor (641-546 B.C.), observed that when amber was rubbed it acquired the power of attracting bits of paper or other light objects to it. The Greek name for amber is **ēlectron**, and when Gilbert (see § 466) found that many other substances behaved in the same way he called them all **electrics**. The bodies which have acquired this power of attraction are said to be **electrified** or to be **charged with electricity**. In later times it has been shown that *any* two different bodies when rubbed together become electrified.

474. Method of Experimenting. A good way to observe the force of attraction is to use a small ball of elder pith or of cork, hung by a silk thread (Fig. 544). When ebonite or sealing wax is rubbed with fur or flannel and held near it the ball is drawn towards it.*

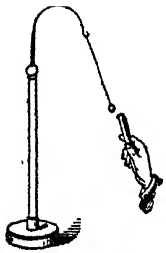


FIG. 544.—A pith ball on the end of a silk thread drawn towards the electrified rod.

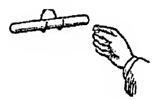


FIG. 545.—The electrified rod moves towards the hand.

It can also be shown that the electrified body is itself attracted by one that has not been electrified. Let us rub an ebonite rod and hang it in a wire stirrup supported by a silk thread (Fig. 545). If the hand (or other body) be held out towards the suspended rod the latter will turn about and approach the hand. A rod of glass when rubbed with silk acts similarly.

475. Electrical Repulsion. Suppose, however, we allow the pith ball (Fig. 544) to touch the electrified rod. It clings to the rod for a moment and then flies off. If the end of the rod is pushed near to it, the ball moves away. There is repulsion between the two. Next, rub a glass rod with silk and hold it to the pith ball. It is attracted. Thus the ebonite now repels the pith ball, but the glass attracts it.

Also, two pith balls, both of which have touched either rubbed glass or rubbed ebonite and are therefore similarly electrified, will be found to repel each other; while a pith ball which has touched an electrified glass rod will attract one which has touched an electrified ebonite rod.

Again, hold a rubbed ebonite rod near the suspended rubbed ebonite rod (Fig. 545); they repel each other. Two

*In these experiments the substances should be thoroughly dry. They succeed better in winter since there is much less moisture in the air then. Special care is required in
litioned

glass rods behave similarly. If, however, we hold a rubbed ebonite rod near the rubbed glass rod there is attraction between them.

476. Two Kinds of Electrification. It is evident from these experiments that there are two kinds of electrification or of electrical charge, and it is customary to call that produced on glass when rubbed with silk, **positive**; that produced on ebonite or sealing-wax when rubbed with flannel or fur, **negative.** The pith ball on touching the glass was repelled and must, therefore, have become charged positively. For a similar reason the ball which touched the ebonite must have acquired a negative charge.

The foregoing and numberless other experiments allow us to formulate the following Law:

Electrical charges of like kind repel each other, those of unlike kind attract each other.

477. Conductors and Non-conductors. We may rest a piece of electrified ebonite on another piece of ebonite or on dry glass, or sulphur or paraffin, and it will retain its electrification for some time; but if it is wiped with a damp cloth, or simply with the hand, it loses its electrification at once. The ebonite, the glass, the sulphur and the paraffin are said to be non-conductors of electricity; while the damp cloth and the hand are said to be conductors of electricity, the electric charge escaping freely by way of them.

If we hold a piece of brass tube in the hand and rub it with fur or flannel or silk, it will show no signs of electrification; but if we fasten it to an ebonite handle and flick it with dry cat's fur, it will be negatively electrified. Approach it to a suspended rubbed ebonite rod (Fig 545) and it will repel the rod. In the first case the brass was electrified, but the electrical charge immediately escaped to earth by way of the experimenter's body. In the second case the escape was prevented by the ebonite handle, and the metal remained

electrified. It is to be noted, too, that a non-conductor exhibits electrification only where it is rubbed, while in a metal the charge is spread all over its surface.

Those substances which lead off an electrical charge quickly are called **conductors**, while those which prevent the charge from escaping are called **non-conductors or insulators.** If a conductor is held on a non-conducting support, it is said to be **insulated.** Thus, telegraph and telephone wires are held on glass insulators; and a man who is attending electric street lamps often stands on a stool with glass feet, and handles the lamps with rubber gloves.

But there are different grades of conductors and insulators, as is shown by the following list:

Good Conductors: metals, including mercury.

Fair Conductors: the human body, solutions of bases, acids and salts in water, wet wood, carbon.

Poor Conductors: dry paper, cotton, dry wood, leather.

Bad Conductors or Good Insulators: glass, porcelain, sealing-wax, paraffin, sulphur, quartz, celluloid, bakelite, mica, silk, shellac, rubber, gases, and oils generally.

478. Nature of Electricity; the Electron Theory. It has already been stated (in § 164) that an atom of matter consists of a positively charged nucleus and a number of electrons. When a body is in its normal or unelectrified state, the sum of the negative charges on the electrons just balances the positive charges on the nuclei. It is considered that electrons are able to wander about from atom to atom in a conductor while the positively charged nuclei remain in position. Moreover, electrons can pass from one solid body to another.

We are now able to apply the idea of electrons to "explain" the phenomena which we have observed. When the ebonite and cat's fur were rubbed together, the ebonite became negatively charged, which means that it obtained an extra supply of electrons from some outside source. Did these electrons

come from the cat's fur? If so, the cat's fur should be lacking the number of electrons which the ebonite has gained, and should exhibit a positive charge. This is found to be actually the case. (§ 488). On the other hand, the glass rod lost electrons to the silk and consequently showed a positive charge. **A negatively charged body is one which has a surplus of electrons; a positively charged body has a deficit of electrons.**

Electrons pass readily from one part of a conductor to another, while in insulators this movement takes place with great difficulty.

479. The Gold-leaf Electroscope. The purpose of an electroscope is to detect an electric charge and to determine whether it is positive or negative. A metal rod with a knob or a disc at the top (Fig. 546) extends through a well-insulated cork into a flask. From its lower end two leaves of gold or of aluminium leaf hang by their own weight. The rod may pass through a glass tube, well coated with shellac, which is inserted through the cork. The flask should be also varnished with shellac, as this improves the insulation greatly. If a charge, either positive or negative, is given to the electroscope, the two leaves, being charged with electricity of the same kind, repel each other and separate.

Fig. 546.—The gold-leaf electroscope.

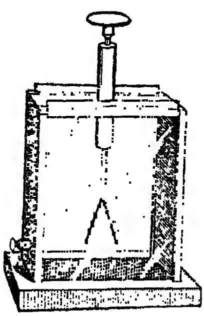


Fig. 547.—Another form of the gold-leaf electroscope.

Another pattern of this electroscope is shown in Fig. 547. The protecting case is of wood with front and back of glass. The sides of the case are lined with tin-foil, to which a binding-post is connected. By this the case may be joined to earth and thus be kept constantly at zero potential

(see § 493). The rod supporting the leaves passes through a block of unpolished ebonite or other good insulator, and the small disc on top may be removed if desired.

480. Charging the Electroscope. The electroscope may be charged by touching a charged body to the knob, or by connecting it to the knob by a conducting wire. But sometimes it is more convenient to use a **proof-plane** (Fig. 548), which is simply a small metal disc on an insulating handle. This is touched to the charged body and then to the knob of the electroscope.

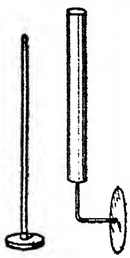


FIG. 548. Proof-planes.

If the body which touches the electroscope is negatively charged, some of its surplus electrons will pass to the knob and then down to the leaves. On the other hand, if a positively charged body touches the knob, some of the electrons in the knob-leaf system pass to the positively charged body in an attempt to re-establish the balance between electrons and nuclei.

On being charged by contact, then, the electroscope acquires the same kind of charge as is on the charging body.

The simple instrument illustrated in Fig. 549, which may be constructed by anyone, will be found to be convenient for charging a body by contact. It consists of a celluloid tube lined at one end with metal which extends beyond the end of the tube. The other end of the tube may be held in the hand, since celluloid is a good non-conductor, but an insulated handle is desirable. This may be simply insulating tape wrapped about the tube.

In the design shown in Fig. 549 the tube, made from sheet celluloid, is about an inch in diameter, and a brass tube within it ends in a brass cap.

When the celluloid is rubbed with cat's fur or flannel it acquires a negative charge, and a negative charge appears

on the cap. The cap will give a negative charge to any object which touches it. If the celluloid is rubbed with a

FIG. 549.—A charging apparatus.

piece of automobile tubing it acquires a positive charge, but the action is not so dependable.

A fuller explanation of the charger is given in § 486.

Another method of charging the electroscope is described in § 485.

481. A Detector of Electrification—Neon Bulb. convenient detector of electrification though not so sensitive as the electroscope, is a neon bulb (Fig. 550). It looks like an ordinary lamp bulb. Within it are two metal plates *a*, *b* close together, one of which is connected to the central terminal *c*, the other to the terminal *d*. The air from the bulb has been removed and a little neon gas admitted. If either terminal touches an electrified body a spark jumps between the plates *a*, *b* and illuminates the bulb with red light.

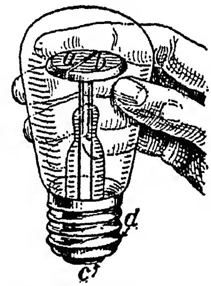


FIG. 550.—A neon bulb.

The neon bulb is very useful in electrical experimenting—for example, in testing spark-plugs in a gasoline engine when it is running.

CHAPTER LXX

ELECTRIFICATION BY INDUCTION

482. Electrification by Induction. In the previous chapter it was shown how to charge a body with electricity by contact, but the same result can be obtained in another way. Let us slowly bring a rubbed ebonite rod towards the knob of the electroscope. The leaves are seen to separate even though the rod be a foot or more away. Some of the electrons in the knob have been repelled to the leaves by the negative charge on the ebonite. This gives the leaves an excess of negative electricity and they repel one another. This experiment shows that the mere presence of an electrified body is sufficient to produce electrification in neighbouring conductors. The charge is said to be produced by **electrostatic influence or induction.** As soon as the charged body is removed the leaves collapse again because the electrons which were driven away from their nuclei are attracted back into their former position as soon as the disturbing influence disappears.

This experiment also impresses the fact that an electrified body exerts an action on bodies in the space about it. This space is called its **electrical field of force.** It can be shown, too, that the magnitude of the force exerted depends on the material filling the space. For instance, if the electrified body is immersed in petroleum the force it exerts on another body is only about one half that in air. Indeed, it is believed that the force exhibited is due to actions in the surrounding medium, which is known as the **dielectric.**

483. Testing the Charge on a Body. Suppose we have an electrified body and wish to test the nature of its charge.

First, place a known charge on the electroscope; then bring up the unknown charge very slowly and watch for the first movement of the leaves. If the charge to be tested is of the same kind as that on the electroscope, the leaves will diverge still farther; if of the opposite kind, the leaves will come together. The reason is obvious.

Caution. If the unknown charge is great enough and is opposite in kind to that on the electroscope, it is possible to reverse the charge on the leaves by bringing the unknown charge close to the knob. For this reason it is important to watch for the *first* movement of the leaves.

484. Nature of Induced Electrification. Let A and B (Fig. 551) be two metallic bodies placed near together on well-insulated supports.* Charge A negatively by the charging rod (§ 480) or in any other way.

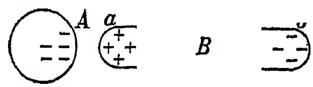


FIG. 551.—Explaining induced electrification.

First, touch A with a proof plane and carry it to the electroscope knob. The leaves will show a separation. Repeat and get a greater separation. Next, touch the proof plane to a, that end of B nearest A, and carry it to the electroscope. The leaves come closer together, showing that the charge on the end a is positive, that is, of the opposite kind to that on A.

Next, touch the proof-plane to the end b, which is farthest from A, and convey the charge to the electroscope. It makes the leaves diverge further, showing that the charge is of the same kind as that on A.

We find, therefore, that the two ends have charges of opposite signs, the charge on the end of B nearest to A being of the opposite sign to that on A. It is to be observed, also, that the electrification on B does not in any way diminish the charge on A.

485. Charging by Induction. In order to charge a body —an electroscope, for instance—by induction proceed as follows.

*These may be tin cans on paraffin blocks.

1. Rub an ebonite rod with cat's fur and bring it near the knob of the electroscope. Electrons are driven to the leaves which diverge (Fig. 552, *a*).

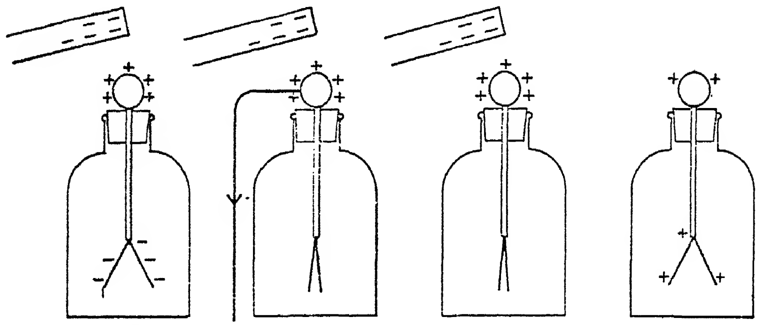


FIG. 552.—Steps in charging an electroscope by induction.

2. Keeping the rod in the same place, touch the knob with a wire joined to the ground* or touch it with a finger. The electrons now have a path by which they can get farther from the rod; they run to earth and the leaves collapse (Fig. 552, *b*).

3. Remove the ground connection (Fig. 552, *c*).

4. Finally take away the rod. The positive charge (*i.e.* deficit of electrons) spreads to the leaves and they diverge again. The electroscope is charged positively. (Fig. 552, *d*)

If we had used a glass rod rubbed with silk the electroscope would be charged negatively.

486. The Electrophorus. By means of this instrument, which was invented by Volta in 1775, we can electrify a conductor without using up the instrument's original charge.

It consists of a cake *A* of ebonite or of resinous wax, and a metal cover† *B*, of rather smaller diameter, provided with an insulating handle. (Fig. 553.)

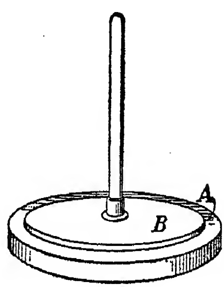


FIG. 553.—The electrophorus.

First, the cake is rubbed with cat's fur, and thus it obtains a negative charge. Then the cover is put on and touched with the finger, if it is lifted up by the handle, after removing the finger, it will be

*A water-pipe or a radiator. †A wooden disc covered with tin-foil.

found to be positively charged, and if it is presented to the knuckle a spark, sometimes half-an-inch long, is obtained, and the cover is discharged. The gas may be lighted with this spark; and if the cover be presented to the knob of an electroscope, the latter will be charged. It may also be tested with the neon bulb (§ 481). The process may be repeated any number of times without renewing the charge on the cake.

The action is explained thus: When the cover is placed on the cake, which is a non-conductor, it rests upon it on a few points only and so does not remove its charge. But the negative charge on A induces on the lower face of B a positive charge, repelling to the upper face a negative charge, which escapes to earth through the body when the finger touches it; therefore, when the cover is lifted it has a positive charge.

QUESTIONS AND PROBLEMS

1. Each time the cover is discharged energy disappears; where does it come from?

2. Lift the cover without previously touching it with the finger and bring a neon bulb to it. Is there a flash? Put the cover back and let it stand for some minutes and test again. Any flash now? Explain. Is the charge positive or negative?

3. Following the usual procedure, touch the cover and lift it off and then present the neon bulb to it. Compare the flash now with that in question 2. Why is it brighter?

487. Explanation of the Charging Rod. We are now prepared to explain the action of the charging rod described in § 480. A longitudinal section of the rod is shown in Fig. 554.

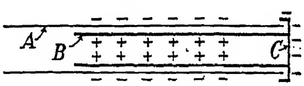


Fig. 554.—Section of charging rod.

When the celluloid tube A is rubbed with cat's fur it acquires a negative charge, *i.e.*, where the rubbing takes place there is a surplus of electrons. These act on the electrons in the brass tube B, repelling some of them to the cap C, which is thus given a negative charge, while that portion of the tube B opposite the rubbed portion of A has a shortage of electrons and is said to be positively charged. When the cap C touches a conducting body the electrons from the cap rush off to the body and give it a negative charge.

488. Charges Produced by Friction Equal and Opposite. In § 478 it was stated that the cat's fur becomes positively charged when used to rub ebonite. We can prove this experimentally, as follows:

Experiment. Place a metal can, large enough to hold the cat's fur, on the plate of an electroscope (Fig. 555). Rub the ebonite and the cat's fur together and place both in the can. No motion of the leaves takes place. Remove the ebonite without touching the can with the hand. The leaves diverge, showing that the fur is charged. Replace the ebonite again and the leaves fall. The charges on the cat's fur and ebonite must, therefore, be equal in amount and opposite in kind.

FIG. 555.—Can on electroscope.

489. Charges Reside on the Outer Surface. That an electric charge is located on the outside of a conductor may be demonstrated by the following experiments:

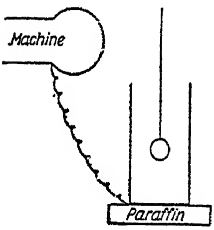


FIG. 556.—A tall metal vessel joined to an electrical machine. Removing the wire disconnects it.

Experiments. 1. Place a tall metal vessel on a good insulator (Fig. 556), and electrify it by a charging rod, or an electrical machine (§ 499). Disconnect from the machine. Lower a metal ball, suspended by a silk thread, into the vessel and let it touch the inner surface. Then apply the ball to the electroscope; it shows no charge. Next, touch the ball to the outside of the vessel and test with the electroscope. It now shows a charge. Finally, charge the ball by the machine, then lower it into the metal vessel and touch the inner surface with it. Then test the ball with the electroscope. It will be found that its charge is entirely gone; it was given to the metal vessel and is now on its outer surface.

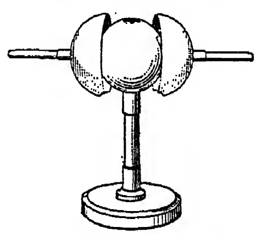


FIG. 557.—Apparatus to show that the charge resides only on the surface of a conductor.

2. In Fig. 557 are shown a metal sphere on an insulating stand, and two hemispheres with insulating handles which just fit over it. First, charge the sphere as strongly as possible. Then, taking hold of the insulating handles, fit the hemispheres over it, and then remove them. If now the sphere is tested with the electroscope, no trace of electricity will be found on it.

490. Distribution of the Charge; the Action of Points. Though the electric charge resides only on the outer surface of a conductor, it is not always equally densė all over it. The distribution depends on the shape of the conductor, and experiment shows that the charge is greater at sharp edges. In Fig. 558 is illustrated the distribution of an electric charge on bodies shaped like *a*, *b*, *c*.

FIG. 558.—Showing the distribution of an electric charge on conductors of different shapes.

The force with which a charge tends to escape from a conductor increases with the density of the charge, and it is for this reason that a pointed conductor soon loses its charge. If a pointed wire is placed on a conductor attached to an electrical machine, the electrified air particles streaming from it may blow aside a candle flame (Fig. 559); or an "electric whirl" (Fig. 560), nicely balanced on a sharp point, when placed on an electrical machine is made to rotate by the reaction as the air-particles are pushed away from the points. It rotates like a lawn-sprinkler.

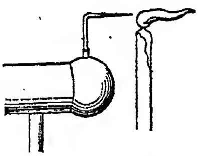


FIG. 559.—"Electric wind" from a pointed conductor blowing aside a candle flame.

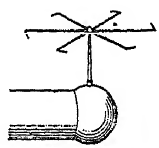


FIG. 560.—The 'electric whirl" rotates by the reaction from the electric

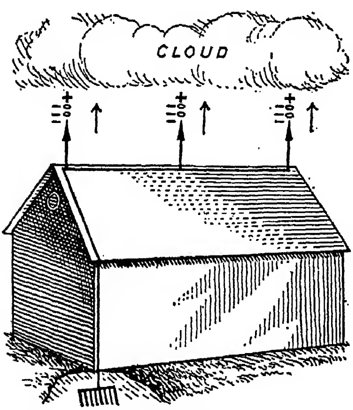


FIG. 561.—Negatively charged air particles are passing from the rods to the cloud.

491. Lightning-Rods. In a thunder-storm the clouds become charged with electricity and by induction a charge of the opposite sign appears on the surface of the earth just beneath. Suppose that the cloud (Fig. 561) has a positive charge. The points of the lightning rods will acquire a very dense negative charge and consequently the air particles

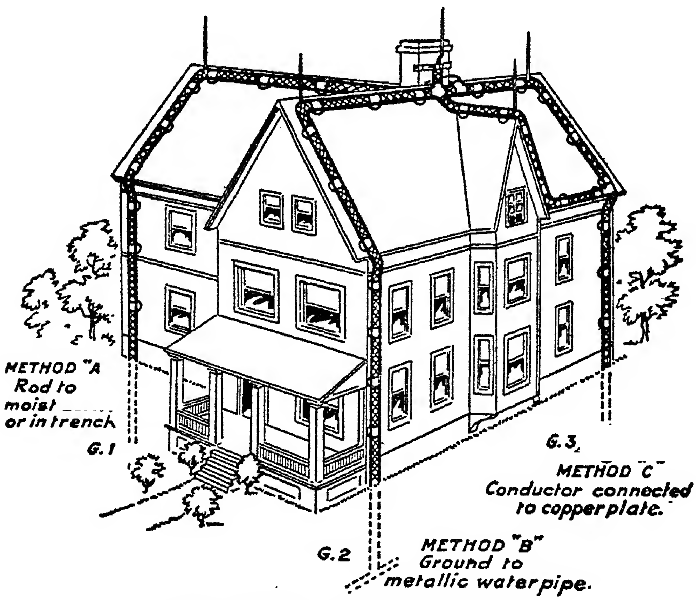
in contact with the points will be come negatively charged and will be repelled from the points and attracted by the cloud. Every negatively charged air particle which reaches the cloud neutralizes some of its charge. In most cases the charge on the cloud will be neutralized in this way without a flash of lightning occurring.

If, however, the force of attraction between the charges on the cloud and the rods is great enough, there may be a very sudden rush of electrons across the intervening space, with the result that great heat is developed and the building is "struck by lightning." The wires running from the rods to the ground are, however, good conductors, and do not become sufficiently heated to set fire to the building. On the other hand, if the building is not equipped with rods, the sudden rush of electrons through the relatively poor conducting materials of which it is constructed usually generates sufficient heat to set the building on fire.

It is evident, then that the lower end of a lightning-rod should be buried deep enough to be in moist earth always, since dry earth is a poor conductor.

QUESTION

Why should the lightning rods terminate in sharp points?



A HOUSE PROTECTED BY LIGHTNING RODS

This house is protected in accordance with the Ontario Government Regulations. Note the five point terminals and three types of ground connections.

An excellent and interesting pamphlet on "Lightning, its Origin and Control" by George F. Lewis may be obtained from the Ontario Fire Marshal's Office, Toronto.

CHAPTER LXXI

POTENTIAL, CONDENSERS, MACHINES

492. Electric Potential. We have learned how to give an electric charge to a body. Suppose *A* and *B* (Fig. 562), to be two metal bodies (tin cans will serve) on insulated stands and let us give a charge to *A*, leaving *B* uncharged. Then let us join *A* and *B* by a wire held by an insulated handle. We know that some action takes place between *A* and *B* and that *B* also becomes electrified. We say there is a flow of electricity from one body to the other.

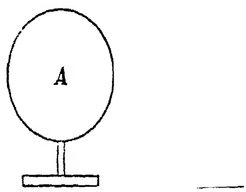


FIG. 562.—Two metal spheres on insulating supports.

Again, let us touch *A* or *B* with a wire which is joined to earth; the body loses its charge and we realize that something has passed between the body and the earth.

Next, consider the two tanks *A* and *B* in Fig. 563. Water will flow from *A* to *B* through the pipe *C* connecting them if the water is at a higher level in *A* than in *B*; or, what amounts to the same thing, if the hydrostatic pressure at *a* is greater than that at *b*. The tank *B* may already have more water in it, but the flow does not depend on that. It is regulated by the difference between the pressures at the two ends of the pipe and it will continue until these pressures become equal.

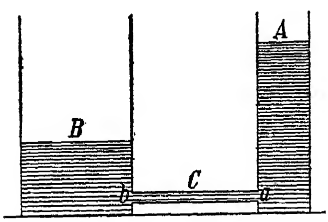


FIG. 563.—Water flows from the higher level in *A* to the lower level in *B*.

Again, when the attendant at a garage connects his tank of compressed air to the tire of a car air flows from the tank

into the tire because the pressure in the tank is greater than that in the tire.

Still further, when two bodies at different temperatures are brought together, there is a flow of heat from the body at the higher temperature to that at the lower temperature.

In the same way, electricity flows through a conductor if the **electrical pressure** or **potential** is greater at one place than at another.

We see, then, that the term potential in electricity corresponds to pressure in hydrostatics and to temperature in the study of heat. If two bodies which are at different potentials are joined by a conductor, there will be a flow, or a **current** of electricity through the conductor until the potentials are equalized.

Potential difference is usually measured in **volts**, a definition of which is given in § 534. See also § 537.

493. Zero of Potential. In stating levels or heights we usually refer them to the level of the sea. The ocean is so large that all the rain which it receives does not appreciably alter its level. In a somewhat similar way, the earth is so large that all the electrical charges which we can give it do not appreciably alter its electrical level or potential, and so we take the potential of the earth to be our zero of potential.

Lake Superior is 602 feet above the level of the sea, and the Dead Sea, in Palestine, is 1,300 feet below it. There is a continual flow from Lake Superior to the ocean; and if a tube joined the two, there would be a flow from the ocean to the Dead Sea.

Consider the four tanks in Fig. 564. The levels of A and B are above, and those of C and D below, that of the earth. A flow would take place from A or B to the earth, or from the

earth to C or D, or from any one tank to another at lower level.

Bodies which are charged positively are arbitrarily considered to be at a potential higher than that of the earth, and those charged negatively to be at a potential below that of the earth. The larger the positive charge on a body is the higher is its potential; the greater the negative charge the lower is its potential.

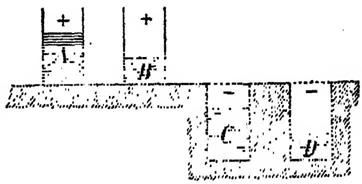


FIG. 564.—Water flows from the higher level in A to the lower level in B.

494. The Electrostatic Voltmeter. The simple electroscope can be used to indicate electrical potential since the degree of divergence of the leaves will vary with the potential of whatever body is connected to the knob. A similar instrument, calibrated to read directly in volts, is shown in Fig. 565. A light aluminium pointer A is pivoted at B on the metal support C which also carries the scale D. This support passes through on ebonite insulator E and has a binding-post F on its upper end. The case of the voltmeter is of metal and is provided with a binding-post G, by which it can be joined to earth to bring it to zero potential. The body whose potential (relative to the earth) we wish to measure is joined to F. The support C and the pointer A acquire the same kind of charge and the pointer is repelled from the support. Such voltmeters can be constructed to measure either very great or very small potentials.

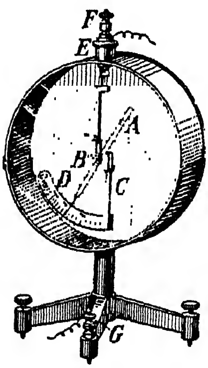


FIG. 565.—Electrostatic voltmeter.

495. Electrical Capacity. Conductors of similar shapes but of different sizes have different capacities for electric charges. What this depends on is illustrated in the following experiments.

Experiments. 1. Consider the two metal spheres in Fig. 562. Charge the larger body A and then join A and B momentarily by an insulated wire, as described in § 492. The two bodies are now at the same potential.

Now test each with a neon bulb. The flash obtained on touching

A is much stronger than that from *B*, and we are led to believe that the charge on *A* was greater than that on *B*. Remembering that the electric charge resides only on the outer surface of a conductor, we conclude that the electrical capacities of two conducting bodies of the same shape are dependent on the areas of their outer surfaces. It should be remarked, however, that the capacity of a body depends to some extent on its shape, not just on the area of its surface.

2. In Fig. 566 *A* and *B* are two metal plates on insulating bases. They may be of tin-plate about 12 inches square, bent at the bottom and resting on paraffin blocks, *C*, *C*, with metal blocks, *D*, *D*, to keep them in place. First let *B* be at some distance from *A*, and charge *A*. The greater the charge, the higher the potential and the wider the gold-leaves diverge. Continue charging until the leaves are far apart.

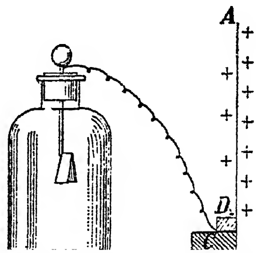


FIG. 566.—Showing the distribution of an electric charge on two metal plates near together.

Then, with the plate *B* joined to earth, push it up towards *A*. As the plates get nearer together, the leaves begin to fall, showing that the potential of *A* has fallen because of the presence of *B*. If now we increase the charge on *A* by means of a charging rod, we shall find that several times the original amount of electricity must be added to *A* in order to obtain the original separation of the leaves, that is, to raise it to the original potential.

This experiment shows that the electrical capacity of a conducting body is increased as the distance to the opposite induced charge is decreased.

The explanation of this action is as follows: Let the charge on *A* be positive. The potential of the plate *A* can be considered as due to the mutual forces of repulsion existing between the charges on it. As the plate *B* approaches *A*, the negative charges which have been formed on *B* by induction (§ 485) exert forces of attraction on the charges on *A* tending to counteract the mutual forces of repulsion. The potential of the plate *A* is thereby reduced which is indicated by the falling of the leaves.

3. Next, push the plates *A* and *B* near together, and charge the plate *A* until the separation of the leaves is quite decided. Now insert between *A* and *B* a sheet of thick plate glass, sliding it along *B*, being careful not to touch *A*, and observe the effect on the electroscope. The leaves come

closer together, showing that the potential has fallen and the capacity has increased. Ebonite or paraffin may be used instead of the glass, but the effect will not be so pronounced.

This shows that the capacity of a charged body may be increased by substituting another insulating medium for air. The insulating medium is called the dielectric.

It should be remembered that the distribution of electricity on the system made up of plate A and the attached electroscope and on plate B depends very decidedly on the distance of B from A.

496. Electrical Condensers. The apparatus used in the last experiment is a simple form of a device known as a **condenser.** Other forms are illustrated in Figs. 567, 569, 570, 571. By using thin sheets of mica or of waxed paper in place of air between the plates they may be much closer without fear of a discharge between them for any potential difference to which they may be subjected. The capacity of the condenser is therefore increased not only on account of the dielectric used but also because of the much smaller distance between the plates.

The capacity of a condenser using glass as a dielectric averages somewhere about 6 times that of the same condenser when air is the dielectric. This number is called the **dielectric constant** for glass. The greater the dielectric constant, the greater is the capacity.

Values of Some Dielectric Constants

Air	1.0	Paraffined paper	2·1 to 2·5
Glass	5·4 to 9.9	Ebonite	2·7 to 2·9
Mica	5·6 to 6.6	Sulphur	4·0 to 4·2

497. Leyden Jar. This is one form of condenser. It consists of a wide-mouthed bottle (Fig. 567), the sides and the bottom of which, both within and without, are coated with tin-foil to within a short distance from the neck. The glass above the tin-foil is varnished to maintain the insulation.

Through a wooden stopper passes a brass rod, the upper end of which carries a knob, the lower a chain which touches the inner coating of the jar. The two coatings form the two plates of the condenser, the glass being the dielectric.

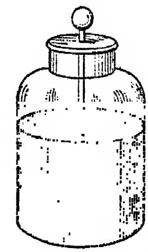


FIG. 567.—A Leyden jar.

To charge the jar the outer coating is connected to earth (or held in the hand), and the knob is joined to an electrical machine. To discharge it, connection is made between the inner and the outer coatings by discharging tongs (Fig. 568). Usually the discharge is accompanied by a brilliant spark and a loud report. (It is wise not to pass the discharge through the body.)

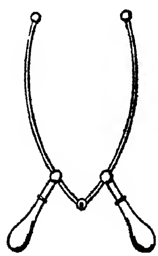


FIG. 568. — Discharging tongs. The handles are of glass or of ebonite.

Condensers used in electrical experiments are often made of a number of sheets of tin-foil separated from one another by sheets of paraffined paper or mica. Alternate sheets of the tin-foil are connected together, as shown in Fig. 569. By this means a large surface area, and consequently large capacity, can be obtained in a small volume. The condenser shown can be considered the equivalent of four two-plate condensers.

FIG. 569.—A plate condenser.

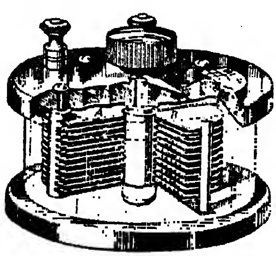


FIG. 570.—A variable air condenser.

Condensers are used extensively in line and wireless telegraphy and telephony. A variable air condenser of the type used in wireless communication is shown in Fig. 570. As the moving plates B are rotated out from between the fixed plates A, the effective area of the plates becomes less and the capacity decreases.

498. Electrolytic Condenser. This condenser is of quite a different form and gives a large electrical capacity in a small space. The essential parts of such a condenser are illustrated in Fig. 571. The positive electrode is an aluminium sheet R coiled into a spiral. A cross-section of R is shown at r. It is supported in a metal container C by means of an insulating bushing B. The container C acts as the negative electrode and a conducting solution with basic properties fills C. The surface of this electrolyte surrounding R acts as one plate of the condenser system.

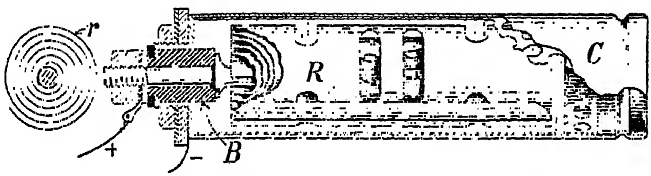


FIG. 571.—Essential parts of an electrolytic condenser.

After assembling the condenser a small current of electricity is passed through it and this causes the formation of a thin oxide layer on the aluminium sheet R. This layer, which is less than one millionth of a centimetre in thickness, acts as the dielectric of the condenser, and on account of its extreme thinness a large capacity is obtained with a small plate area. When being used the condenser must be connected so as to have the electrode R positive, since the oxide layer breaks down if the polarity is reversed.

499. Toepler-Holtz Influence Machine. The ordinary electrical machines are simply convenient contrivances for utilizing the principle of influence illustrated in the electrophorus (§ 486).

In Fig. 572 is shown a Toepler-Holtz machine. In it are two parallel glass plates, A and D, the former being fixed while the latter can be rotated in front of it. Upon the back of A are two pieces of tin-foil C, C', called *armatures*, which are covered by paper sectors. Upon the front of the moving plate are 6 or 8 tin-foil discs, a, b, c, . . . , called carriers, each having a brass button attached at its centre. Two brass rods, one at the lower end of C, the other at the upper end of C', are bent around from the back to the front of the plates. One end is connected to an armature,

while the other bears a metal brush which rubs on the brass buttons as they pass by. Upon the rods E, E' are metal combs with sharp teeth, which point toward the carriers but do not touch them. These rods are

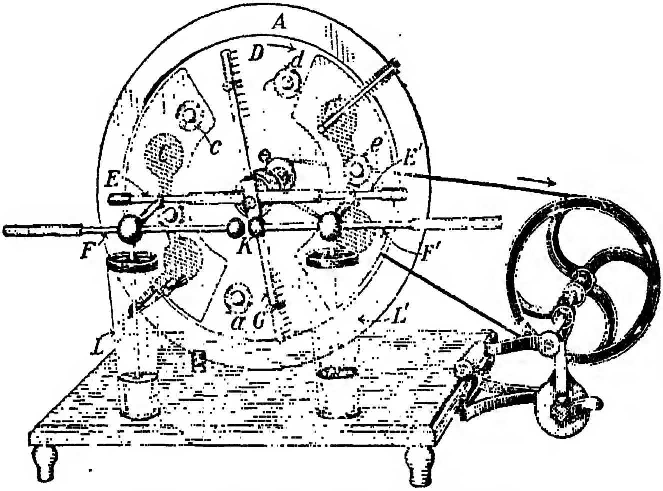


FIG. 572.—The Toepler-Holtz electrical machine.

connected to the discharging knobs K, between which the sparks pass when the machine is in operation. The insulated neutralizing rod G has a brush at each end. These touch opposite pairs of carriers as they pass. Two Leyden jars L, L' are usually added and when they are charged powerful sparks are produced.

500. The Action of the Machine. The action of the machine can be explained by means of the diagram (Fig. 573) in which, for clearness, the two discs are represented as though they were two glass cylinders, one within the other, the outer one being fixed and the inner one rotating in the direction of the arrow.

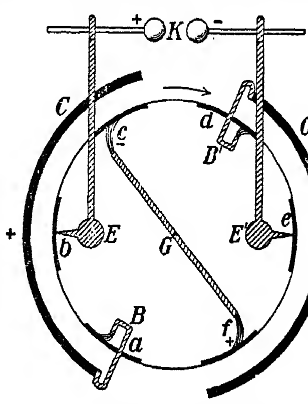


FIG. 573.—Diagram of the Toepler-Holtz machine.

Suppose a, one of the carriers, has a small positive charge. On passing the brush B a portion of its charge will be given to the armature C. The carriers c and f are (momentarily) connected by the rod G, and the charge on C will induce a negative charge on c at one end of G and a

positive charge on f at the other end of G. As the carriers c and f move forward the former will give up some of its negative charge to C' and the latter some of its positive charge to C. In this way the charges on the armatures rapidly increase and these by induction increase the charge on the carriers.

Now, the carriers still retain a portion of their charges after passing the brushes B, B' and this will be collected from them by the metal combs E, E'. These are connected to the knobs K between which, when they are charged to a sufficiently high potential, a spark will pass.

Usually the machine is self-starting. If it refuses to start, a piece of rubbed ebonite or sealing-wax held opposite c or f will give the charge necessary to start it. After the machine has "picked up" the two armatures assist each other through the neutralizing rod G.

501. Electrostatic Generator. Very recently an electrical generator of great size and of a novel type was constructed. Its object was to supply enormous energy in concentrated form which could be hurled against the nuclei of atoms in the effort to break them up. This sort of investigation is referred to in §§ 164, 640.

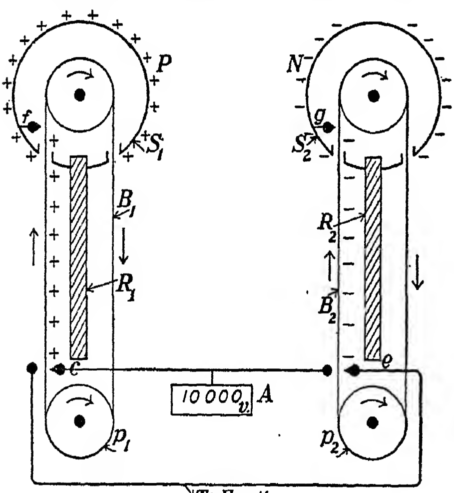


FIG. 574.—Diagram to explain the Van de Graaff electrostatic generator.

The principle of the machine will be understood from the diagram (Fig. 574). S_1, S_2 are two hollow metal spheres on insulating supports R_1, R_2. B_1, B_2 are belts of insulating material (silk, paper) passing around pulleys, the lower ones p_1, p_2, being driven by motors, with the belts moving in the direction indicated by the arrows. A is a transformer-rectifier set and when connections are made as shown in the diagram, positive electricity is "sprayed" from the point of the conductor c upon the belt B_1, while negative electricity is sprayed from the point e upon the belt B_2. The charge on B_1 is carried up through an opening in the sphere S_1 and is collected by the point f and led over to the sphere upon the outside surface of which it appears. The negative charge at

e is conveyed by belt B_2 and appears on the outer surface of S_2. Thus P and N are the two terminals of the machine with a great potential difference between them. If they are made to approach, violent discharges will take place between them.

In Fig. 575 is shown the great machine erected at Round Hill, near Boston, Mass. The spheres are 15 ft. in diameter, constructed from

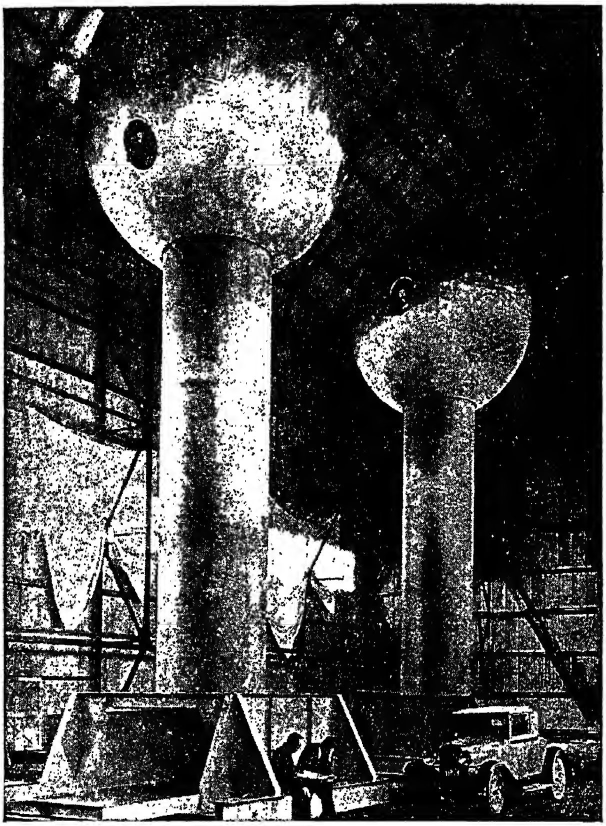


FIG. 575.—Van de Graaff electrostatic generator erected at Round Hill, Mass.

sheets of aluminium alloy $\frac{1}{4}$-inch thick, pressed into shape and shipped in sections—like parts of an orange peel. The supports are made from a shellac compound and are 6 ft. in diameter and 24 ft. high. They are mounted on trucks which can be pushed along rails out into the open air. The belts are of paper 4 ft. wide and travel about a mile a minute. Considerable electricity at very high potential is generated.

QUESTIONS AND PROBLEMS

1. If two insulated bells (Fig. 576) are joined to the coatings of a charged Leyden jar while a small brass ball is suspended between them by a silk thread, the ball will swing back and forth, causing the bells to ring. Explain the action. What will happen to the charge on the jar?

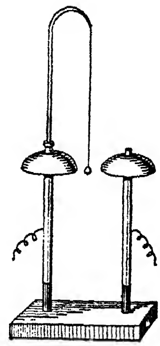


Fig. 576.—Electric chimes.

2. A piece of brass mounted on an ebonite handle is rubbed on a piece of cloth. How would you test the charge on the brass by using (*a*) a pith-ball electroscope, (*b*) a gold-leaf electroscope? Why use the ebonite handle?

3. How would you use an electroscope to test whether a moistened silk thread is as good an insulator as the same thread when dry?

4. Describe three experiments that could be performed to show that magnetism is essentially different from electricity.

5. What experiments would you perform to show that there are two kinds of electricity?

6. Why are the glass or porcelain insulators used on telephone and electric light lines made in the shape of an umbrella (Fig. 577)?

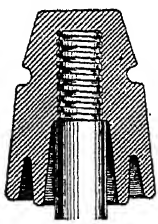


Fig. 577.—An insulator.

7. Telephone cables frequently contain hundreds of wires insulated from one another by dry paper, the whole being enclosed in a lead sheath. Of what use is the sheath? A small hole through the lead soon interferes seriously with the transmission of speech. Explain.

8. A lightly insulated field telephone cable which was buried under a road worked well for a day or two and after that the signals became very faint. The section across the road was dug up and carried over the road on poles and the line worked properly again. Explain why the fault occurred.

9. Use the electron theory to explain why charges reside on the outside of a charged conductor.

10. Explain the action of the lightning-rods (Fig. 561) when the cloud is charged negatively.

REFERENCES FOR FURTHER INFORMATION

Bragg, W. L., *Electricity*, Chapter I.
Reynolds, *Electricity and Magnetism*, pages 152-179.
Saunders, *A Survey of Physics*, Chapter 20.

CHAPTER LXXII

THE ELECTRIC CURRENT

502. The Electric Current. As explained in § 492, when two bodies at different potentials are joined by a conductor, there is a passage of electricity from one to the other. For example, if the terminals of an influence machine are connected by a wire, electrons, each of which bears a negative charge will flow along the wire from the negative to the positive terminal. We speak of electric charges in motion as a **current of electricity.**

According to the electron theory we should think of the current as flowing from the negative to the positive terminal. Unfortunately, before the electron theory was generally accepted, it was agreed to consider the current as flowing from the positive to the negative terminal, and, since many of the rules governing electrical action are based on this assumption, we shall still follow the conventional method.

This at first sight may appear confusing, but the difficulty clears up when we realize that a flow of positive charges in one direction would produce the same final result as a flow of electrons (negative charges) in the opposite direction. Whichever way we consider it, the flow would tend to neutralize the charges on the terminals and to bring them to the same potential.

503. The Voltaic Cell. A current of electricity may be generated in other ways than by the flow of charges produced by friction or induction. If a zinc plate and a copper plate are dipped into dilute sulphuric acid and connected by a conductor, as shown in Fig. 578, a current of electricity will flow

through the conductor. The presence of the current can be shown by winding copper wire about a glass tube and inserting a knitting needle therein. When the connections are made, the knitting needle is magnetized.

The current in the wire connecting two bodies which have been charged as described in the previous chapter is momentary, but the current in the conductor joining the zinc and copper plates can be shown to be continuous.

This arrangement of zinc and copper plates immersed in dilute sulphuric acid for the purpose of producing an electric current is one of the simplest forms of what is known as the **Galvanic or Voltaic Cell.**

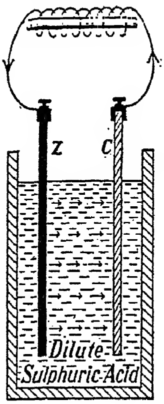


Fig. 578.—Simple voltaic cell with plates joined by a wire made into a coil.

The cell is named from the men most immediately concerned in its development. Galvani* discovered by accident that the discharge of an electric machine connected with a skinned frog produced convulsions in the legs; and on further research he found that the same effect could be produced without the electric machine, by simply touching one end of a branched fork of copper and silver wires to the muscles in the frog's leg, and the other end to the lumbar nerves (Fig. 579). He attributed the results to "animal magnetism."

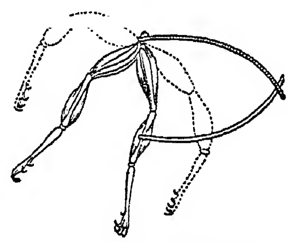


Fig. 579.—Galvani's experiment.

Volta,† a fellow-countryman, conceived that the electric current had its origin, not in the frog's legs, but in the contact of the metals. In his investigations he found that when discs of copper and zinc were separated by a disc of cloth moistened with common salt brine, and joined externally by a conductor as in Fig. 580, a current passed through the circuit. Later, he substituted zinc and copper strips for the discs and immersed them in dilute sulphuric acid.

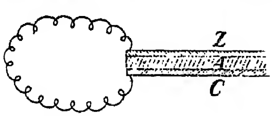


Fig. 580.—*Z*, zinc; *C*, copper; *A*, cloth moistened with brine.

*Aloisio Galvani (1737-1798), a Physician and Professor of Anatomy in the University of Bologna.

†Allesandro Volta (1745-1827), Professor of Physics at the University of Pavia, Italy.

504. An Electric Circuit. A complete circuit is necessary for a steady flow of electricity. This circuit comprises the entire path traversed by the current, including the external conductor, the plates, and the fluid. The current is regarded as flowing from the copper, or positively charged plate, to the zinc, or negatively charged plate, through the external conductor, and from the zinc to the copper plate through the fluid (Fig. 578).

505. Oersted's Experiment. With an electric circuit as illustrated in Fig. 578, containing a coil of wire encircling a steel needle, the current flowing through the coil magnetizes the needle. This important principle was discovered by Oersted* in 1819. He had been making some experiments in the hope of discovering an identity between electric force and magnetic force, when, almost by accident, he placed the wire joining the plates of a voltaic battery over and parallel to a magnetic needle. He was astonished to see the needle turn and set itself almost at right angles to the wire. When he reversed the direction of the current the needle turned in the opposite direction (Fig. 581). If the battery is held over the wire, the needle is deflected, thus showing that the current flows through the battery too.

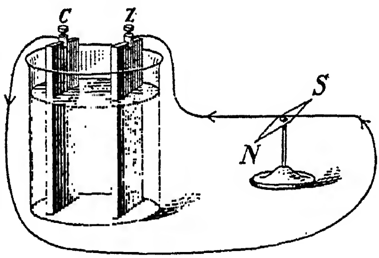


FIG. 581.—Oersted's experiment.

506. Rules for Direction of Current and Motion of Needle. By holding the wire first over and then under the needle we find that, no matter in which direction the current is flowing, the needle always sets itself in a definite direction.

Two rules have been given to help one to determine the direction in which the needle will point:

*Hans Christian Oersted (1777-1851), Professor in the University of Copenhagen.

1. Swimmer Rule. Imagine yourself swimming in the wire with the current and facing the needle; then the *N*-pole of the needle will be deflected toward your left hand.

2. Right Hand Rule. Imagine the wire conductor grasped by the right hand with the fingers encircling the conductor and the thumb pointing in the direction of the current flow; then the fingers represent the direction in which the *N*-pole of the needle is deflected.

FIG. 582.—The right hand rule.

507. Detection of an Electric Current. Oersted's experiment furnishes a ready means of detecting an electric current. A feeble current, flowing in a single wire over a magnetic needle, produces a very slight deflection; but if the wire is wound into a coil, and the current made to pass several times in the same direction, either over or under the needle, or, better still, if it passes in one direction over it and in the opposite direction under it, the effect will be magnified (Fig. 583). Such an arrangement is called a **Galvanoscope.** It may be used not only to detect the presence and the direction of currents, but also to compare roughly their strengths, by noting the relative deflections produced.

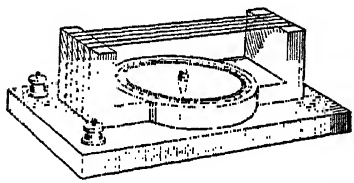


FIG. 583.—Simple galvanoscope. The wire passes several times around the frame, and its ends are joined to the binding-posts.

Exercises. 1. Use the right hand rule to show why a current flowing through a loop of wire should deflect a compass-needle placed between the upper and lower part of the loop more than the same current flowing through a single wire. In what circumstances would the loop produce less effect than the single wire?

2. In the galvanoscope in Fig. 583 suppose the current in the wires which are in sight flows from the left to the right end of the instrument. Use the right hand rule to determine which end of the needle (*N* or *S*) is deflected toward the observer.

For more accurate measurements of current strength, ammeters are employed. The value of the current in a circuit is usually expressed in terms of a unit called an **ampere,** which will be accurately defined in Chapter LXXV.

508. Analogy between Electric Currents and the Flow of Water. Flow of electricity in a closed circuit is in many respects analogous to the flow of water in a system of pipes. In order to maintain a flow of water some device, such as a pump, must be used to set up pressure differences in the circuit.

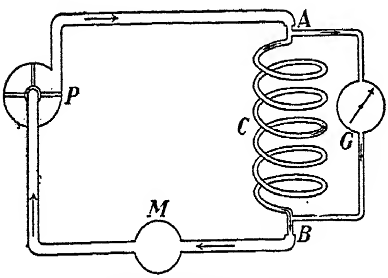


FIG. 584.—Simple water circulating system with a rotary pump.

Let Fig. 584 represent a system of water pipes with a rotary pump *P* driving a stream of water through a coiled pipe *C*. In order to measure the rate of flow a meter *M* is connected in series with the coil, that is, in such a way that the water which passes through the coil also passes through the meter. The position of *M* is immaterial; the water may flow through the meter either before or after it flows through the coil.

To measure the pressure difference at the ends of the coil a pressure gauge *G* is connected in parallel with the coil, as shown in Fig. 584. The gauge may be joined to any two points of the coil, and the reading on the gauge will vary with the points of the circuit to which it is connected. Tests with a system such as described show that the rate of flow through the pipes increases as the pressure difference between two points on the coil is increased.

509. Simple Electric Circuits. In Fig. 585 is shown a battery consisting of two cells (described in § 524) joined in series, a lamp *L* and a switch *S* for closing the circuit and

starting the current or for breaking the circuit and stopping the current. The battery corresponds to the pump in Fig. 584 and the lamp corresponds to the coiled pipe C. The battery, lamp and switch are all joined in series.

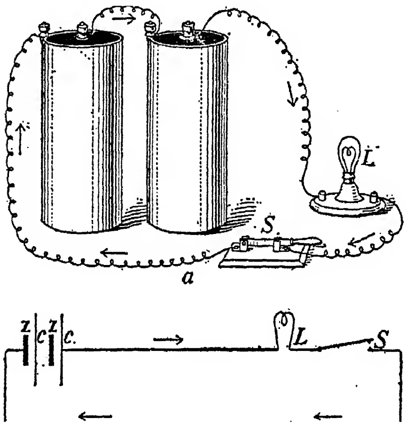


FIG. 585.—A simple electric circuit consisting of a battery of two cells, a lamp and a switch all joined in series. (a) shows the actual apparatus, (b) is a simplified diagram of the circuit.

Electrical circuits are usually represented by simplified diagrams. In Fig. 585 *a* is a sketch of the actual apparatus, while (*b*) is the simplified diagram. In it *z* and *c* stand for zinc and carbon or zinc and copper.

In Fig. 586 is sketched a battery B, a lamp L, an ammeter A, a voltmeter V and a switch. The connections are clear. Comparing this circuit with the water system in Fig. 584, the battery B corresponds to the pump P, while the lamp L, the ammeter A, joined in series, and the voltmeter V joined in parallel, with the lamp, correspond respectively to the coil C, the meter M and the pressure gauge G.

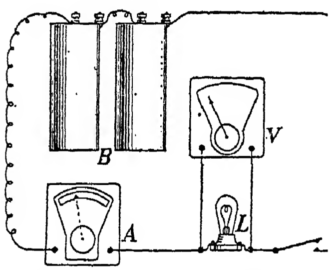


FIG. 586.—An electrical circuit containing a battery, a lamp, an ammeter, a voltmeter and a switch.

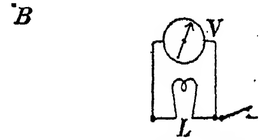


FIG. 587.—A simplified diagram of the circuit sketched in FIG. 586.

The simplified diagram corresponding to Fig. 586 is given in Fig. 587. It shows clearly how the conducting wires are joined.

510. Conductors in Series and in Parallel. The electrical connections for a battery joined up with two lamps L_1 and L_2 in series are indicated in Fig. 588. Observe that if either lamp is burnt out or removed, the circuit is broken and the current ceases to flow. The miniature lamps used in Christmas decorations are arranged in groups, the lamps in a group being joined in series. If any lamp fails all the lamps in that group fail. In an electric street-car the lamps which light it are sometimes connected in groups; if one lamp burns out or is removed all the lamps in its group go out.

Fig. 588.—Diagram showing lamps in series.

In Fig. 589 the method of connecting the two lamps L_1, L_2 in parallel is shown. In this case if one of the lamps is removed the current continues to flow through the other. The lamps, sweeper, toaster and other appliances ordinarily in use in house circuits are connected in parallel so that each one may be switched in or out of the circuit without interfering with the others.

Fig. 589.—Diagram showing lamps in parallel.

CHAPTER LXXIII

CHEMICAL EFFECTS OF THE ELECTRICAL CURRENT

511. Electrolysis. So far, in speaking of conductors, we have had reference mainly to metals or other solids; but an electric current may be made to flow through liquids as well. We have had a hint of this in discussing the direction of the current in the voltaic cell (§ 504).

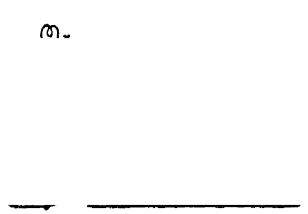


Fig. 590.—Diagram of apparatus for experiments on the passage of an electric current through liquids.

The behaviour of liquids when an attempt is made to pass an electric current through them may be illustrated by simple experiments as follows.

Experiment. Let us arrange apparatus as in the adjoining diagram (Fig. 590). Two monel (or other) metal plates P, P, are supported in a beaker B and are connected in series with a lamp L and a switch S to terminals T in a dynamo circuit.

First, fill the beaker with pure distilled water and close the switch. The lamp does not light up which shows that pure water is a poor conductor of electricity. There is not enough current passing through to light the lamp. Now add a few drops of sulphuric acid to the water. Almost at once the lamp begins to glow and soon it gets brighter. This shows that a solution of sulphuric acid is a conductor of electricity. Many other acids act similarly.

Again start with pure water in the beaker and throw in a lump of sugar. It dissolves but the lamp shows no effect. Now throw in a small lump of common salt. Soon there is a glow in the lamp and before long it is burning brightly. A solution of common salt is a conductor. Similarly with other salts and bases. If we try alcohol we find it is not a conductor.

We thus learn that liquids may be divided into two classes:

(1) Conductors, which are called **electrolytes.**
(2) Non-conductors, which are non-electrolytes.

512. Electrolysis of Water. For an accurate study of the passage of an electric current through an electrolyte

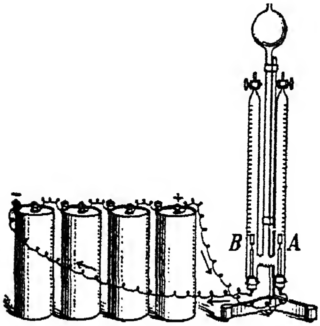


Fig. 591.—Electrolysis of acidulated water.

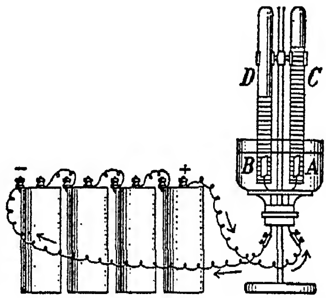


Fig. 592.—Electrolysis of water, alternative apparatus.

the apparatus illustrated in Fig. 591 may be employed. In the lower ends of the two similar tubes are rubber stoppers through which run wires ending in platinum plates. The tubes are filled with water containing a small amount of sulphuric acid and the wires are joined to the battery as shown.

The two plates by which the current enters and leaves the electrolyte are called **electrodes,** the one by which it enters being the **anode** (*A* in the figure), and that by which it leaves, the **cathode** (*B* in the figure). The apparatus in Fig. 591 is often called a **voltameter.** In Fig. 592 is shown a simpler form of voltameter, test tubes replacing the graduated tubes in Fig. 591.

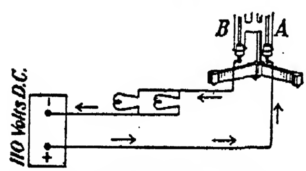


Fig. 593.—Electrical circuit for a voltameter connected to a D.C. circuit

If a 110-volt direct current circuit is available the connections given in Fig. 593 will be found to be more satisfactory. The current strength can be altered by varying the size of the lamps in the bank of lamps connected in series with the voltameter.

As the electric current passes through the solution, gases form at the electrodes and collect as bubbles which rise to the top of the graduated tubes, displacing the water. The ratio of the volumes of gas formed is 2 to 1 for water. Allowing some of each gas to escape into a test tube and testing, by means of a lighted splinter, it is found that the gas with double volume is hydrogen while the other is oxygen. In this experiment the result is the decomposition of water into its constituent elements, hydrogen and oxygen. The function of the sulphuric acid in this reaction is discussed in (§ 515).

Secondary Reactions Occurring in Electrolysis. If the acidulated water is replaced by a solution of common salt (NaCl), chlorine appears at the anode, but the sodium atoms, which have parted with their charges to the cathode, instead of combining to form molecules, displace hydrogen atoms from molecules of water in order to form sodium hydroxide. Hence, hydrogen, and not sodium, is liberated at the cathode. The presence of the hydroxide in solution can be shown by adding sufficient red litmus to colour the solution. As soon as the current begins to pass, the liquid about the cathode is turned blue. The bleaching of the litmus about the anode indicates the presence of chlorine.

The foregoing experiment is typical of a large number of cases of electrolytic decomposition where secondary reactions, depending on the chemical relations of elements involved, take place.

513. Molecules and Ions. According to the commonly accepted theory the molecules of an electrolytic salt or acid, when in solution, become more or less completely **dissociated.** The respective parts into which the molecules divide are known as **ions.** When, for example, common salt is dissolved in water, a percentage of the molecules (NaCl) break up to form sodium (Na) and chlorine (Cl) ions. Similarly, if sulphuric acid is diluted with water, some of its molecules (H_2SO_4) dissociate into hydrogen (H) ions and sulphate (SO_4) ions.

A definite charge of electricity is associated with each ion, and when it loses this charge it ceases to be an ion. The

hydrogen and sodium atoms, and the atoms of metals in general, as ions, bear positive charges, while chlorine atoms and sulphate ion are types, respectively, of the elements and radicals which bear negative charges.

514. Laws of Electrolysis. Faraday discovered that the masses of the substances liberated in the process of electrolysis are dependent only on the strength of the current and the time during which it flows, and that when the same current is made to flow through several electrolytes the masses of the various substances liberated from these electrolytes are proportional to their **chemical equivalents.**

His Laws of Electrolysis were formulated in 1833. They may be summed up in the following statements:

1. The mass of the ions liberated at an electrode is proportional to the strength of the current and to the time the current flows.

2. The masses of the elements separated from the electrolyte in the same time by the same electric current are proportional to their chemical equivalents.

The chemical equivalent of an element is equal to its atomic weight divided by its valency. For any given element this may vary with the other elements with which it is associated. Copper is a good example of this effect. In cupric compounds such as copper sulphate the chemical equivalent equals $\frac{1}{2} \times 63 \cdot 6$, *i.e.*, $31 \cdot 8$ grams, while in cuprous compounds the valency equals one and the chemical equivalent equals $63 \cdot 6$ grams.

515. Theory of Electrolysis. The fundamental phenomena of electrolysis as enunciated in Faraday's laws are readily explained on the basis of the modern electrical theories regarding the constitution of matter.

In the case of sulphuric acid dissolved in water there is much evidence, obtained in various ways, to show that a large portion of the molecules break up into ions. In this process of dissociation, two extra electrons are attached to the sulphate radical SO_4, giving it a negative charge whereas

each hydrogen atom is robbed of an electron and hence is positively charged.

When a potential difference is maintained, by means of a battery or dynamo, between electrodes immersed in this electrolyte the sulphate ions (SO_4^{--})* are attracted to the anode and, when they come in contact with it, the extra electrons are given up and an SO_4 radical is formed. In a secondary reaction following this, the (SO_4) radical replaces oxygen in water so that oxygen is liberated at the anode and the quantity of acid in the solution remains constant. The hydrogen ions are attracted to the cathode where they lose their charge and form atoms and hydrogen is thus liberated at the cathode. The electrons deposited on the anode are transferred through the circuit by the external potential difference and, for each pair of electrons given up to the anode from a sulphate (SO_4^{--}) ion, two electrons leave the cathode, neutralizing two hydrogen ions and liberating two hydrogen atoms. Hence the electricity transferred through the circuit is proportional to the quantity of electrolyte decomposed, and also the masses of the elements separated out are proportional to their chemical equivalents.

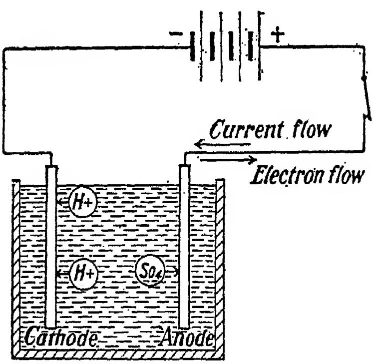


FIG. 594.—Illustrating current flow and electron flow.

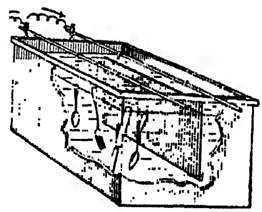
In this connection it is important to note that the direction of the electron flow is opposite to that of the conventional direction of current flow as indicated in Fig. 594.

516. Electroplating. Advantage is taken of the deposition of a metal from a salt by electrolysis in order to cover one

*The addition of the two minus signs means that this radical is charged negatively.

metal with a layer of another, the process being known as **electroplating.**

Consider, as an example, the process of silver-plating. The objects to be plated are immersed in a bath containing a solution of silver salt, usually the cyanide (AgCN). A plate of silver is also immersed in the bath (Fig. 595). A current from a battery or dynamo is then passed through the bath, from the silver plate (the anode), to the objects (the cathode). The positively charged silver ions are urged to the objects, and on giving up their charges, are deposited as a metallic film upon them. Meanwhile the negatively charged cyanogen (CN) ions migrate towards the silver plate, from which they attract into solution additional silver ions. Thus the metal is transferred from the plate to the objects, while the strength of the solution remains constant.



The process of plating with other metals is similar to silver-plating. The electrolyte must always be a solution of the salt of the metal to be decomposed; the anode is a plate of that metal, and the cathode the object to be plated.

For copper-plating, the bath is usually a solution of copper sulphate; for gold- and silver-plating, a solution of the cyanides; and for nickel-plating, a solution of the double sulphate of nickel and ammonium.

517. Electrotyping. Books are now usually printed from electrotype plates instead of from type, as the type would soon wear away. An impression of the type is made in a wax mould, the face of which is then covered with powdered plumbago to provide a conducting surface upon which the metal can be deposited. The mould is then flowed with a solution of copper sulphate, and iron filings are sprinkled over

it. The iron displaces copper from the sulphate, and the plumbago surface is thus covered with a thin film of copper The iron filings are washed off, and the mould immersed in a bath of nearly concentrated copper sulphate solution, slightly acidulated with sulphuric acid. The copper surface is then connected with the negative terminal of a battery or dynamo, and a copper plate, which is connected with the positive terminal, is immersed in the bath.

When the layer of copper has become sufficiently thick it is removed from the bath, backed with melted type-metal and mounted on a wooden block. The face is an exact reproduction of the type or the engraving.

518. Electrolytic Reduction of Ores; Electrolysis Applied to Manufactures. Electrolytic processes are now extensively used for reducing certain metals from their ores. A soluble, or fusible salt is formed by the action of chemical reagents, and the metal is deposited from it by electrolysis. For example, aluminium is reduced in large quantities from a fused mixture of electrolytes. Sodium is prepared in a similar manner.

The metallurgist also resorts to electrolysis in separating metals from their impurities. Copper, for example, is refined in this way. The unrefined copper is made the anode in a bath of copper sulphate, and the pure copper is deposited at the cathode, while the impurities fall to the bottom of the bath. The copper secured by this method is called electrolytic copper and is over 99·9 per cent. pure. It is especially valuable for the manufacture of wires for electrical circuits.

Currents of electricity are also employed in the preparation of many chemical products for commercial purposes. Caustic soda and bleaching liquors are manufactured on a large scale by electrolytic means.

CHAPTER LXXIV

VOLTAIC CELLS; STORAGE CELLS

519. The Essential Parts of a Voltaic Cell. We have found that when a plate of zinc and a plate of copper are immersed in dilute sulphuric acid and connected by a conducting wire (Fig. 596), a current of electricity flows through the wire because a difference in potential is maintained between the plates. But voltaic cells may be formed with other pairs of plates and with other electrolytes as exciting fluids. The essential parts of an ordinary voltaic cell are two different conducting plates immersed in an electrolyte which acts chemically on one of them.

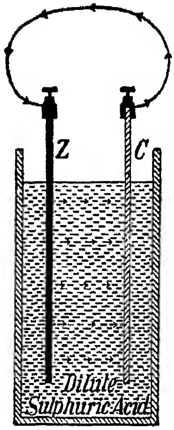


Fig. 596.—Simple voltaic cell.

520. Chemical Action of a Voltaic Cell. When plates of copper and chemically pure (or amalgamated) zinc are placed in dilute sulphuric acid to form a voltaic cell, the zinc begins to dissolve in the acid but the action soon ceases. If, however, the upper ends of the plates are connected by a conducting wire, or are touched together, the zinc continues to dissolve in the acid, forming zinc sulphate, and hydrogen is liberated at the copper plate.

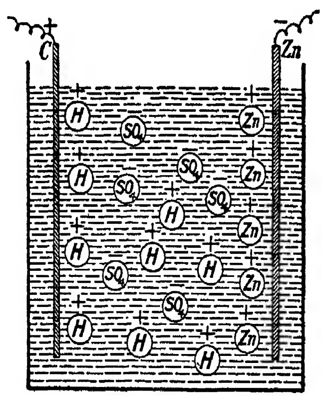


Fig. 597.—Diagram illustrating the theory of the action of a voltaic cell.

These chemical changes take place within the cells in accordance with the same principles as the changes in the

electrolytic cell as described in § 512, the main difference being that in the electrolytic cell the source of the current is outside the cell, while in the voltaic cell the current originates within the cell itself.

According to the modern theory each atom of a metal consists of a positively charged nucleus surrounded by a sufficient number of outer electrons to neutralize its positive charge (see § 164). In the case of a copper atom the number of outer electrons is 29, and in a zinc atom the number is 30. Of these electrons 2 in each atom of the metal are comparatively free to move and are called free electrons.

In the case of the voltaic cell zinc ions, which consist of zinc atoms minus 2 electrons per atom, go into solution, thus leaving a negative charge on the zinc plate. The action on the copper plate is much less pronounced and consequently if the plates are joined by a conductor (as in Fig. 596), electrons flow through the conductor to the copper plate. The positively charged hydrogen ions in the solution migrate to the copper plate where their charges are neutralized by the electrons which were transferred over from the zinc plate. The hydrogen atoms combine into hydrogen molecules and collect as bubbles of gas on the copper plate. One can say that in the changes just described chemical energy is transformed into electrical energy.

When the circuit is open, just enough action takes place to keep the plates at a certain difference of electrical level or potential, but when the plates are connected by a conductor the current flows and the zinc is continually consumed.

521. The Electromotive Force of a Voltaic Cell. The difference of potential between the plates of a cell, when the circuit is open, is considered as causing the current to flow in the circuit formed when the plates are joined by a con-

ductor. Now in the study of mechanics the motion of a body is due to force applied to it; and similarly, when there is motion of electricity in a circuit it is said to be due to **electromotive force.** In the case of the voltaic cell the electromotive force (E.M.F.) is equal to the difference of potential between the plates on open circuit.

The E.M.F. of a cell containing a given electrolyte depends on the nature of the plates. Thus the E.M.F. of a zinc-carbon cell is about one and a half times as great as that of the zinc-copper cell, when dilute sulphuric acid is the electrolyte.

When the materials used are constant, the E.M.F. is independent of the size and the shape of the plates or their distance apart.

Theoretically, a comparatively large number of substances might be selected as plates to construct a voltaic cell, but, as we shall see, some combinations are much better than others.

Experiment. Let us study this question experimentally. Take plates of zinc, copper, tin and carbon and form cells by placing them, two at a time, in dilute sulphuric acid.

First use the zinc and copper plates and connect the cell so formed to a galvanoscope or a voltmeter, noting the amount and the direction of the deflection. Then substitute in succession the tin and the carbon plate for the copper plate, and from the direction of the deflection determine which is positive and which is negative in each case. Record also the amount of the deflection in each case.

Next, test copper-tin, copper-carbon and tin-carbon cells. The results will be as follows:

Zinc −, Copper +	Copper +, Tin −
Zinc −, Tin +	Copper −, Carbon +
Zinc −, Carbon +	Tin −, Carbon +

Also, it will be found that the zinc-carbon pair gives the greatest deflection.

We learn from our tests that zinc is negative, no matter which of the other three metals is used with it; that tin is positive when used with zinc but negative with copper and carbon; that copper is positive to zinc

and tin but negative to carbon; while carbon is positive to each of the others.

We can write these four elements in a series, thus:

Zinc, Tin, Copper, Carbon,

in which any element becomes the positive plate of a cell when used with any element appearing before it in the series, but it becomes the negative plate if used with a metal appearing after it in the series. Moreover, the potential difference between the metals in any pair depends upon their relative positions in the series. Such a series is known as an **electromotive,** or **potential,** series.

A more comprehensive series obtained by a more extended investigation is the following:

Magnesium, Zinc, Iron, Lead (clean), Tin, Copper, Silver, Gold, Platinum, Carbon.

We have noted that a plate of pure zinc when used in a voltaic cell continues to dissolve only when it is connected with the copper plate. Commercial zinc will dissolve in the acid even when unconnected with another plate. The fact that the impure zinc wastes away in open circuit is possibly explained on the theory that the impurities, principally iron and carbon, take the place of the copper plate, and as a consequence currents are set up between the zinc and the impurities in electrical contact with it. Such currents are known as **local currents,** and the action is known as **local action.** Similarly the action of dilute sulphuric acid on zinc is hastened by the addition of some copper turnings.

522. Polarization of a Cell. If the plates of a zinc-copper cell are connected with a galvanoscope, the current developed by the cell will be seen gradually to grow weaker. It will also be observed that the weakening in the current is accompanied by the collection of bubbles of hydrogen on the copper plate. To show that there is a connection between the change in the surface of the plate and the weakening in the current, brush away the bubbles and the current will be found to grow stronger. A cell is said to be **polarized** when the current becomes feeble from a deposition of a film of hydrogen on the positive plate.

The adhesion of the hydrogen to the positive plate weakens the current in two ways. First, it decreases the potential difference between the plates; because the potential difference between zinc and hydrogen is much less than between zinc and copper or carbon. Second, it increases the resistance which the current encounters within the cell, because it diminishes the surface of the plate in contact with the fluid.

Polarization may be reduced by surrounding the positive plate by a chemical agent which will combine with the hydrogen and prevent its appearance on the plate.

523. Leclanché Cell. Practically voltaic cells differ from one another mainly in the remedies adopted to prevent polarization. Several of the forms commonly described have now only historic interest. Of the cells at present used for commercial purposes, the Leclanché, the Daniell and the Dry are among the most important.

The usual construction of the Leclanché cell is shown in Fig. 598. It consists of a zinc rod immersed in a solution of ammonic chloride in an outer vessel, and a carbon plate surrounded by a mixture of small pieces of carbon and powdered manganese dioxide in an inner porous cup. The zinc dissolves in the ammonic chloride solution, and the hydrogen which appears at the carbon plate is oxidized by the manganese dioxide.

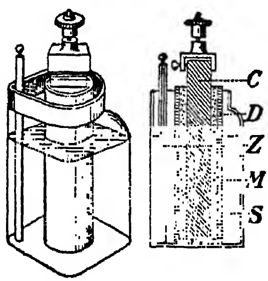


FIG. 598.—Leclanché cell. C, carbon; D, porous cup; Z, zinc; M, carbon and powdered manganese; S, solution of ammonic chloride.

As the reduction of the manganese dioxide goes on very slowly, the cell soon becomes polarized, but it recovers itself when allowed to stand for a few minutes. If used intermittently for a minute or two at a time, the cell does not require renewing for months. For this reason it is especially

adapted for use on electric bell, telephone and other open circuits. Its E.M.F. is about 1·5 volts.

524. The Dry Cell. The so-called dry cell is a modified form of the Leclanché cell. The carbon rod *C* (Fig. 599) is closely surrounded by a thick paste *A*, composed chiefly of powdered carbon, manganese dioxide and ammonic chloride. This is all contained in a cylindrical zinc vessel *Z*, which acts as the negative pole of the cell. Within the zinc container is a lining *L* of cardboard, which acts the same as the porous pot in the Leclanché cell. A small air space is left above the chemicals and the top is sealed by means of a fibre cover.

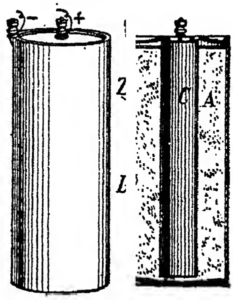


FIG. 599.—A dry cell.

525. Daniell Cell. The Daniell cell consists of a copper plate immersed in a concentrated solution of copper sulphate contained in an outer vessel and a zinc plate immersed in a zinc sulphate solution in an inner porous cup (Fig. 600).

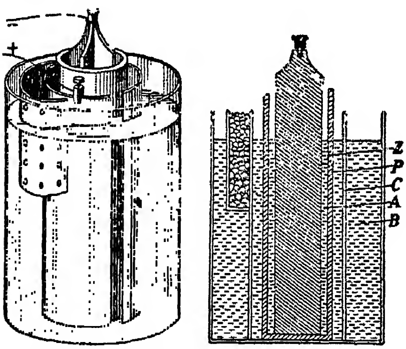


FIG. 600—Daniell cell. *Z*, zinc; *P*, porous cup; *C*, copper; *A*, solution of zinc sulphate; *B*, solution of copper sulphate.

In a form of the Daniell cell known as the Gravity cell the porous cup is dispensed with and the solutions are separated by gravity (Fig. 601). The zinc plate, which is usually of the form shown in the figure, is supported near the top

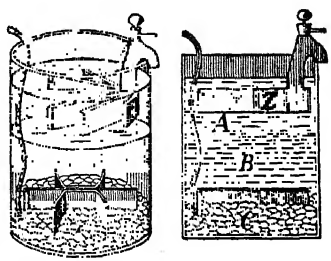


FIG. 601.—Gravity cell. *Z*, zinc plate; zinc sulphate solution; *B*, copper solution; *C*, crystals of copper

of the vessel and the copper plate is placed at the bottom. The copper sulphate, being denser than the zinc sulphate, sinks to the bottom, while the zinc sulphate floats above about the zinc plate. The copper sulphate solution is kept concentrated by placing crystals of the salt in a basket in the outer vessel (Fig. 600), or at the bottom about the copper plate (Fig. 601).

When the plates are connected by a conductor, zinc goes into solution and copper, not hydrogen, is deposited on the copper plate. Polarization is, therefore, avoided, and the difference in potential is constantly maintained.

Accordingly, the Daniell cell is capable of giving a continuous current for an indefinite period if the materials are renewed at regular intervals; but the strength of the current is never very great because the internal resistance is high.

These cells are adapted for closed circuit work, when a comparatively weak current will suffice. The cell is damaged if left on open circuit because copper is deposited on the zinc plate and in the pores of the porous cup. The gravity type has been extensively used on telegraph lines, but in the larger installations the dynamo and the storage battery plants have now taken the place of voltaic cells.

The E.M.F. of the cell is about 1·07 volts.

526. Storage Cells or Accumulators. If lead electrodes are substituted for the platinum in the experiment of § 512, and the battery current is made to pass through dilute sulphuric acid (1 of acid to 10 of water) for a few minutes, hydrogen will be liberated as before at the cathode, and the other lead plate (the anode) will be observed to turn a dark brown, while less oxygen is set free at its surface. The experiment may be readily performed by connecting the battery B,

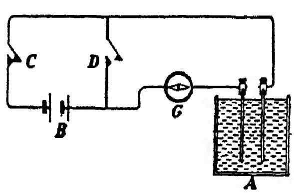


FIG. 602.—An experiment to illustrate the action of a storage cell.

electrolytic cell A, and the galvanoscope G, as shown in the Fig. 602, mercury cups or switches being provided for opening and closing the circuits at C and D. When the circuit is closed at C but open at D, the electrolysis proceeds, and the galvanoscope indicates the direction of the current.

If now the battery is cut out by opening C and the circuit is closed at D, a current will be found to pass through the galvanoscope in a direction opposite to the original current. The electrolytic cell now acts like an ordinary voltaic cell and can be used to ring an electric bell or for any other purpose for which a voltaic cell is used.

This experiment illustrates the principle of action of all **storage cells or accumulators.**

When the current is passed through the dilute acid from one plate to the other, the oxygen freed at the anode unites with the lead, forming an oxide of lead. The composition of the anode is thus made to differ from the cathode, and in consequence there arises a difference in potential between them which causes a current to flow in the opposite direction when the plates are joined by a conductor.

This current will continue to flow until the plates again become alike in composition, and hence in potential.

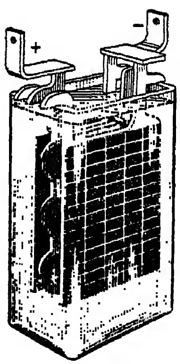


FIG. 603. — A storage ...ith one posi... egative plat... nd three negathree positive and four negative, or even more plates may be used.

527. Commercial Lead Storage Cell. Instead of using plates of solid lead, perforated plates or "grids" are usually employed (Fig. 603). When the cell is purchased in a fully charged condition, the holes in the positive plate are filled with lead peroxide (PbO_2) and those in the negative plate with spongy lead (Pb). Both of these active materials are porous and consequently present a very large surface to the action of the electrolyte. This gives the cell a greater ampere-hour capacity.

During the process of discharge both the plates are converted into lead sulphate, and a part of the sulphuric acid disappears, thus lowering the density of the electrolyte. When the cell is being charged (Fig. 604), the sulphate ions move to the anode and combine with lead sulphate and water to form lead peroxide and sulphuric acid, while the hydrogen ions on arriving at the cathode react upon the lead sulphate forming spongy lead and sulphuric acid; consequently the density of the electrolyte rises again. On account of this a battery hydrometer (§ 46) can be used to determine the general condition of a cell. The specific gravity of the solution in an automobile battery ranges from about 1·28 when fully charged to about 1·15 when completely discharged.

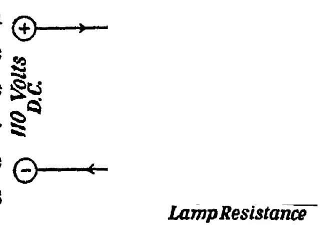


FIG. 604.—Charging a 4-cell (8-volt) storage battery from 110-volt D.C. mains.

The E.M.F. of a fully charged cell is about 2.2 volts. The cell should be re-charged when the terminal voltage has dropped to about 1·8 volts at the normal rate of discharge.

The capacity of a storage battery is measured in **ampere-hours.** For example, an 80 ampere-hour battery should give a current of 1 ampere for 80 hours, or 2 amperes for 40 hours, when freshly charged.

Good lead cells have an efficiency of about 75%, that is, they give out on discharge about three-quarters of the electrical energy used in charging them.

Storage batteries are extensively used in connection with central power stations for emergency purposes. They are also used for automobile lighting and ignition, for wireless work, for driving submarines when submerged, in fire alarm and signal stations and for many other purposes.

528. Edison Storage Cell. In this type of storage cell, which was developed by the great inventor Edison, the positive elements consist of perforated nickel-plated steel tubes filled with a mixture of nickel hydroxide and metallic nickel flakes. The negative elements consist of perforated nickel plated steel frames containing iron oxide. The electrolyte is a 20 per cent. solution of caustic potash. The E.M.F. of the cell is approximately 1·33 volts. The cell is comparatively light in weight and is not as easily damaged as the lead storage cell.

529. Primary and Secondary Cells. The voltaic cells described in the early part of this chapter are known as **primary cells.** A current is available from such cells as soon as the unlike plates are immersed in the electrolyte. A battery of voltaic cells will, of course, cease to give a current when the zinc plates are consumed, and these must be renewed from time to time.

In the storage cell the plates are alike in the beginning, and the differences in composition and potential are produced by an electrolytic process. Accordingly, such cells are known as **secondary cells.** As they can be discharged and recharged daily for a number of years, they furnish a cheap and reliable means of providing electric currents where portable batteries are the most convenient source of supply.

QUESTIONS AND PROBLEMS

1. What transformations of energy take place (1) in charging a storage cell, (2) in discharging it? Is anything "stored up" in the cell? If so, what?

2. Why is it possible to get a much stronger current from a storage cell than from a Daniell cell?

3. When a storage battery is discharged, the density of the electrolyte falls. Could a storage cell be re-charged by adding sulphuric acid?

4. If the capacity of a storage battery is 60 ampere-hours, how long would it give a current of 3 amperes? If its efficiency is 75%, how long would a current of 3 amperes have to be passed through it to re-charge it?

5. A storage battery is used to light 20 incandescent lamps, each requiring 0·4 amperes. If the capacity of the battery is 120 ampere-hours, how long should it light the lamps when fully charged?

CHAPTER LXXV

ELECTRICAL UNITS: AMPERES, VOLTS, WATTS

530. Measurement of Current Strength by Electrolysis. The definite relation between the strength of an electric current and the mass of a substance liberated by it from an electrolyte in a given time furnishes a means of measuring the strength of the current, since a unit current may be taken as the current which liberates a certain mass of a selected element in a unit of time.

The practical unit of current strength universally accepted is the **Ampere** and is defined as **the current which deposits silver at the rate of 0·0011183 grams per second.**

The ampere is originally obtained thus: Consider a current of electricity flowing in a conductor bent into a circle of radius 1 cm. It produces a magnetic field about the wire (see Ch. LXXVII), and that current which exerts on a unit pole at the centre a force of 2π dynes is said to be of unit strength. This unit current is too large for ordinary use and one-tenth of it is called an ampere, which by experiment is found to deposit silver at the rate of 0·0011183 gm. per sec. (A unit magnetic pole is one that, if 1 cm. from a similar pole, repels it with a force of 1 dyne.)

The same current deposits copper at the rate of 0·000329 grams, and hydrogen at the rate of 0·0000104 grams per second. Hence if W_1, W_2, W_3 is the mass in grams of silver, copper and hydrogen, respectively, deposited in t seconds, and I the strength of the current in amperes, then

$$I = \frac{W_1}{t \times 0{\cdot}0011183} = \frac{W_2}{t \times 0{\cdot}000329} = \frac{W_3}{t \times 0{\cdot}0000104}$$

531. Voltameters. An electrolytic cell used for the purpose of measuring the strength of an electric current is called a **voltameter.**

1. **Silver Voltameter.** The cell consists of a platinum bowl, partially filled with a solution of silver nitrate in which

is suspended a silver disc (Fig. 605). When the voltameter is placed in the circuit, the platinum bowl is made the cathode and the silver disc the anode.

When the current has been passed through the solution for the specified time the silver disc is removed, the solution poured off, and the bowl washed, dried and weighed. The increase in weight gives the mass deposited and the current strength in amperes is easily calculated.

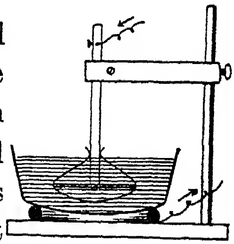


FIG. 605.—A standard silver voltameter. Cathode, a platinum bowl not less than 6 cm. in diameter and 4 cm. deep. It rests on a metal ring to ensure [illegible] Anode, [illegible] silver supported by a silver rod riveted through its centre. Electrolyte, 15 gm. silver nitrate to 85 c.c. water.

Example. Let the original weight of the bowl be 100·0000 gm. and its weight after the current has flowed for 10 minutes be 101·3416 gm.

$$\text{Then } I = \frac{1\cdot3416}{600 \times 0\cdot001118} = 2\cdot00 \text{ amperes.}$$

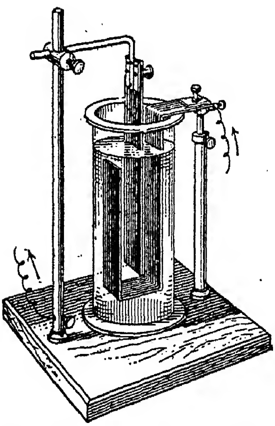


FIG. 606.—A copper voltameter.

2. Copper Voltameter. In the copper voltameter two copper electrodes are immersed in a solution of copper sulphate (100 gm. of copper sulphate to 500 c.c. of water). A common form of the instrument is illustrated in Fig. 606, but two plates of sheet copper provided with binding-posts and placed in a tumbler work very well. The cathode is cleaned with sand-paper or emery-cloth and carefully weighed. It is then placed in position and the current to be measured is passed through the solution for 15 or 20 minutes. The plate is then removed, washed and dried without rubbing, and finally weighed again.

Example. Suppose it is desired to find the current which passes through an automobile headlight lamp when connected to a 6-volt storage battery.

Arrange apparatus as in Fig. 607. P and N are the terminals of the battery, L is the lamp and V the voltameter.

FIG. 607.—Finding the current passing through a lamp.

Let the initial weight of the cathode be 50·342 gm. and the weight after the current has flowed for 15 min. be 51·082 gm.

$$\text{Then } I = \frac{\cdot 740}{900 \times 0\cdot 000329} = 2\cdot 5 \text{ amperes.}$$

3. **Hydrogen Voltameter.** This is simply the apparatus used for the decomposition of water (§ 512). For the purpose of measuring the current, the hydrogen alone is collected in a graduated tube. The current to be measured is passed through the acidulated water until the liquid in the tube stands at the same level as the liquid in the vessel. The time during which the current was passing is then noted. The temperature of the gas and the barometric pressure are also taken. The volume of the hydrogen liberated is read from the graduated tube, reduced to standard pressure and temperature, and the mass corresponding to this volume calculated.

The process of measuring the strength of a current by a voltameter is slow and in ordinary electrical work an ammeter is used. The construction of this instrument is explained in Chapter LXXVIII. Voltameters are employed mainly in standardizing these instruments.

QUESTIONS AND PROBLEMS

1. What weight of (*a*) copper, (*b*) silver will a current of 2 amperes deposit in 1 hour?

2. What weight of (*a*) hydrogen, (*b*) oxygen will be liberated in a water voltameter by a current of 5 amperes flowing for 2 hours?

3. At standard temperature and pressure what volume would the hydrogen and oxygen in the preceding question occupy? (1 c.c. hydrogen at N.T.P. weighs ·0000895 gram.)

4. What current will deposit 1·1899 grams of copper in 10 min.?

test an ammeter it was connected in series with ;
rough which a current of 3 amperes as read by the
;o pass for 50 minutes. The increase in the weight ‹
was 9·8943 grams. Find the error in the ammeter reading.

7. A copper voltameter was connected in series with a storage battery and a wireless valve for 15 minutes. If the deposit weighed 0·5904 grams, what current passed through the valve.

8. How long will it take a current of one ampere to deposit one gram of copper from a solution of copper sulphate?

9. If the electro-chemical equivalent of zinc is ·000339, how much zinc must be used up in a voltaic cell to produce a current of 2 amperes for 15 min.? (Assume that no zinc is lost through local action.)

10. How many ampere-hours should be developed by the consumption in a voltaic cell of 3·051 gm. of zinc?

532. Current and Difference of Potential. We have learned (§ 502) that if there is a difference of potential between two conducting bodies and they are joined by a wire, a current is produced in the wire. Examples of this statement are very familiar. When the little bulb is inserted in a flash-lamp a current passes through the slender filament which becomes white hot and radiates light. In this case the requisite difference of potential is supplied by the battery. When a desk or floor lamp is "plugged into" an electrical outlet the ends of its filament are connected to terminals in a dynamo circuit and the lamp is lighted. In order to keep the lamp burning a constant difference of potential between the terminals must be maintained, and it is the duty of the dynamo to do that very thing. As we know, to drive the dynamo demands power which is supplied by a steam engine or a waterfall. Thus in order to provide electric light, energy is consumed or work is done and for this we have to pay.

Every lamp is designed for a certain difference of potential, which is measured in volts, and a certain strength of current,

which is measured in amperes. This is true for all electric services—such as heaters, motors, etc. The higher the difference of potential and the stronger the current, the greater is the output, or the consumption, of energy.

533. Energy Output in an Electric Circuit. The energy output, or the consumption of energy, in an electric circuit may be further illustrated by means of various combinations of electric lamps in series and in parallel.

Consider a circuit as in the diagram (Fig. 608), consisting

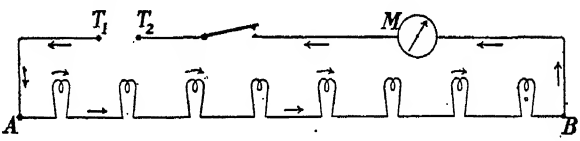


FIG. 608.—Group of eight lamps in series.

of eight precisely similar lamps connected in series to the terminals T_1, T_2 of a dynamo circuit. An ammeter M is shown placed between T_2 and B. It may be between T_1 and A or between any two successive lamps and it will indicate the same number of amperes of current. This shows that the current is the same in every part of the circuit.

The lamps are all the same, *i.e.*, each requires the same difference of potential and the same current to light it properly. The energy consumed in each lamp is the same and the fall of potential between the terminals of each lamp is the same. Neglecting the connecting wires, we may say that if the difference of potential between T_1 and T_2 is 80 volts, the difference of potential between the terminals of each lamp is 10 volts.

Next, consider a circuit with two groups of lamps connected in parallel (Fig. 609), each group being similar to that in the previous case. The difference of potential between the leads A and B is the same as before, but the current now has two paths to go from A to B, namely, by way of group I and

group II, and the strength of the current through each group is the same as through the group in Fig. 608. An ammeter anywhere in group I or in group II will indicate the same

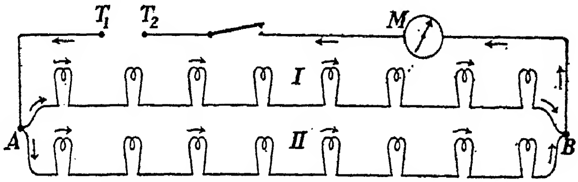


FIG. 609.—Two groups of lamps in parallel.

number of amperes as in the first case. Thus the total current flowing from A to B is twice that in the first case. This double current will be indicated on the ammeter when placed between T_2 and B or between T_1 and A. The energy consumed in this circuit is twice that in the first case.

534. Calculation of Power. In electrical practice the unit employed to express the *rate of output of energy* or the *power* is the watt, which has already been defined in § 128.

The electrical units are so chosen that **if a potential difference (p.d.) of 1 volt is maintained between two points of a conductor and if a current of 1 ampere flows between the points, then the power required to keep the current flowing is 1 watt.**

Having defined the ampere and the watt, we have also defined the volt.

If the p.d. is 110 volts and the current is 20 amperes, the power is $110 \times 20 = 2200$ watts $= 2{\cdot}2$ kilowatts; and if this is provided for 5 hours the energy supplied is $2{\cdot}2 \times 5 = 11$ kilowatt-hours (k.w.h.).

In general terms, if a current of I amperes is supplied at a p.d. of V volts, and W watts is the power required to do it, then

$$W = VI.$$

Another unit of power is the horsepower (h.p.). It is equal to 746 watts, which is approximately 750 watts or $\frac{3}{4}$ kilowatt. Hence, 1 h.p. = $\frac{3}{4}$ k.w. (approx.).

Electrical appliances usually bear a plate which states the p.d. for which they are designed and either the amperes or the watts they require.

QUESTIONS AND PROBLEMS

Services found in a house:

1. Toaster: 110 volts, 5 amperes. Calculate the watts.

2. Portable heater: 110 volts, 660 watts. Calculate the current.

3. Electric iron: 110 volts, 575 watts. What current?

4. Curling tongs: 110 volts, 15 watts. What current?

5. Washing machine motor: 110 volts, 3·6 amperes. What is the power in watts and in h.p.?

6. Three lamps are marked: 110 volts, 25 watts; 120 volts, 40 watts; 115 volts, 60 watts. Find the current in each case.

7. If services 1-6 are supplied at the same time, find the total power in watts and in h.p.

8. A generator (or dynamo) when running at 705 revolutions per minute can deliver 113 amperes at 115 volts. Find the power in k.w. Why is the number of r.p.m. given on the plate on a dynamo?

9. A motor is designed for 60 amperes at 110 volts. Find the power in k.w. ~~and h.p.~~

CHAPTER LXXVI

OHM'S LAW: AMPERES, VOLTS, OHMS

535. Ohm's Law. The strength of a current, or the quantity of electricity which flows past a point in a circuit in one second, depends on two things: (1) the E.M.F. producing the current, and (2) another quantity which is called the "resistance" of the circuit. The exact relation which exists among these quantities was first enunciated by G. S. Ohm in 1826.

He found, as we did in the last chapter, that the strength of the current is the same at all points in the circuit; also that **the current passing through any conductor is directly proportional to the potential difference between its ends.*** He called the constant quantity, obtained by dividing the potential difference by the current the **resistance** of the conductor.

We have then:

$$\text{Resistance of conductor} = \frac{\text{P.D. between ends of conductor}}{\text{Current flowing through conductor}}$$

$$\text{Resistance of a circuit} = \frac{\text{Total E.M.F. in circuit.}}{\text{Current flowing through circuit}}$$

From a practical point of view this is one of the most important generalizations in electrical science. It is known as **Ohm's Law.**

If I is the measure of the current in amperes; R the resistance of the conductor in ohms; and V the difference of potential, in volts, between the ends of the conductor, then according to Ohm's Law

---

*This is true when no change occurs in the physical conditions of the conductors.

$$R = \frac{V}{I}, \text{ or } V = RI, \text{ or } I = \frac{V}{R}.$$

In considering an electrical circuit it is usual to represent the total voltage, or E.M.F., by E and then Ohm's law is written

$$R = \frac{E}{I}, \text{ or } E = RI, \text{ or } I = \frac{E}{R}.$$

536. Demonstration of Ohm's Law. One method is illustrated in Fig. 610. A is a battery connected in series with a variable resistance B, an unknown resistance C (a metre of German silver wire of diameter about ½ mm. serves well) and an ammeter D. A voltmeter E is joined to the ends of C.

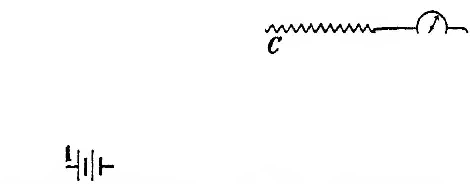


Fig. 610.—Method of demonstration of Ohm's Law.

By reading the ammeter with the voltmeter disconnected we find out the current flowing through the wire. Connecting in the voltmeter shows the potential difference between the ends of the wire. Divide the voltmeter reading by the ammeter reading and record the result.

Next, alter the sliding contact in B. This will change the current flowing through C and the reading on the voltmeter will alter at the same time. As before, divide the voltmeter reading by the ammeter reading and record the result.

Continue this for several more positions of B. Then if the temperature of the wire remains constant, the results will all be equal and the magnitude of the result expresses the resistance of C in ohms.

537. Measurement of Difference of Potential. In the demonstration of Ohm's Law just described the value of the resistance of a conductor was determined by means of a voltmeter and an ammeter. This is a "practical" method.

Other very accurate methods, which are too difficult to be explained here, have been devised for measuring electrical resistance, and it is evident that if we know the resistance R of a conductor and measure the current passing through it, we may compute the potential difference V between its ends from Ohm's Law, since $V = IR$. Standard resistance coils have been constructed for this purpose.

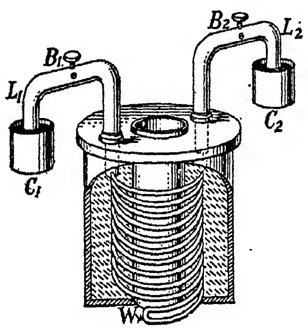


Fig. 611.—Standard ohm resistance.

One form of standard ohm coil is illustrated in Fig. 611. The resistance wire W is wound double into a coil, whose ends are connected to heavy leads L_1, L_2, which themselves end in mercury cups C_1, C_2. This arrangement reduces the resistance of the terminal connections to a negligible amount. Binding posts B_1, B_2 are usually provided from which measurements of potential differences are made.

It is evident that from Ohm's Law the following statement is true:

A volt is that difference of electrical potential which, when steadily applied to a conductor whose resistance is one ohm, will produce therein a current of one ampere.*

PROBLEMS

1. The electromotive force of a battery is 10 volts, the resistance of the cells 10 ohms, and the resistance of the external circuit 20 ohms. What is the current?

2. The difference in potential between a trolley wire and the rail is 500 volts. What current will flow through a conductor which joins them if the total resistance is 1000 ohms?

3. The potential difference between the terminals of an incandescent lamp is 104 volts when one-half an ampere of current is passing through the filament. What is the resistance?

*For a more complete but brief account of electrical units see Chant and Burton's *College Physics*, p. 301.

4. A dynamo, the E.M.F. of which is 4 volts, is used for the purpose of copper-plating. If the resistance of the dynamo is $\frac{1}{100}$ of an ohm, what is the resistance of the bath and its connections when a current of 20 amperes is passing through it?

5. What must be the E.M.F. of a battery in order to ring an electric bell which requires a current of $\frac{1}{10}$ ampere, if the resistance of the bell and connection is 200 ohms, and the resistance of the battery 20 ohms?

6. What must be the E.M.F. of a battery required to send a current of $\frac{1}{100}$ of an ampere through a telegraph line 100 miles long if the resistance of wires is 10 ohms to the mile, the resistance of the instruments 300 ohms, and of the battery 50 ohms, and if the return current through the earth meets with no appreciable resistance?

538. Fall of Potential in a Circuit. If a battery or dynamo is generating a current in a circuit, it is evident that the E.M.F. required to maintain this current in the whole circuit is greater than that required to overcome the resistance of only a part of the circuit. For example, if the total resistance is 100 ohms, and the E.M.F. is 1000 volts, the current in the circuit is 10 amperes. Here an E.M.F. of 1000 volts is required to maintain a current of 10 amperes against a total resistance of 100 ohms; manifestly to maintain this current in the part of the circuit of which the resistance is, say, 50 ohms, an E.M.F. of but 500 volts will be required. This is usually expressed by saying that there is a fall in potential of 500 volts in the part of the circuit whose resistance is 50 ohms.

In general, if there is a closed circuit through which a current is flowing, the fall in potential in any portion of the circuit is proportional to the resistance of that portion of the circuit.

539. Experimental Verification of Fall of Potential. The arrangement shown in Fig. 612 is suitable. *AB* is a metre of bare German silver wire of uniform cross-section stretched alongside a metre-stick and connected in series with a battery *C* and an ammeter *D*. One terminal of the voltmeter *E* is joined to *A* while the other may be touched to different points.

As F is moved along the wire AB, it will be found that the reading of the ammeter does not change but that the potential difference shown by the voltmeter between A and F is directly proportional to the distance AF. (It follows from this, also, that the resistance of a conductor of uniform cross-section is directly proportional to its length.)

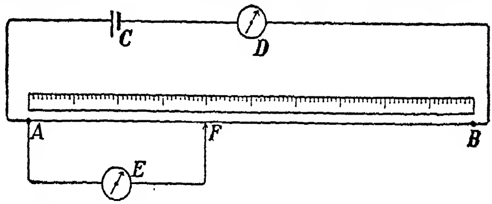


FIG. 612.—Illustration of fall of potential in a circuit.

PROBLEMS

1. Two resistances AB and BC are connected in series and a 100 volt storage battery whose resistance is negligible has its terminals joined to A and C. If the resistance of AB is 9·6 ohms and that of BC is 2·4 ohms, what current will flow through the circuit and what will be the potential difference between A and B and between B and C?

2. The poles of a battery are connected by a wire 8 metres long, having a resistance of one-half ohm per metre. If the E.M.F. of the battery is 7 volts and the internal resistance 10 ohms, find the current in the wire and the p.d. between two points on the wire which are 2 metres apart.

3. The potential difference between the brushes of a dynamo supplying current to an incandescent lamp is 104 volts. If the resistance in the wires on the street leading from the dynamo to the house is 2 ohms, that of the wires in the house 2 ohms, and that of the lamp 204 ohms, what is the fall in potential in (1) the wires on the street, (2) the wires in the house, and what is the potential difference between the terminals of the lamp?

4. A dynamo is used to light an incandescent lamp which requires a current of 0·6 ampere and a potential difference between its terminals of 110 volts. If the wires connecting the dynamo with the lamp have a resistance of 5 ohms, find the potential difference which must be maintained between the terminals of the dynamo to light the lamp properly.

CHAPTER LXXVII

MAGNETIC RELATIONS OF THE CURRENT

540. Discovery of Electromagnetic Phenomena. The discovery by Oersted of the effect of an electric current on the magnetic needle (§ 505) gave a decided impetus to the study of electromagnetic phenomena. The investigations of Arago, Ampère, Davy, Faraday and others during the next ten years led to the discovery of practically all the principles that have had important applications in modern electrical development.

541. Magnetic Field Due to an Electric Current. In 1820, a year after Oersted's great discovery, Arago proved that a wire carrying a strong current had the power to lift iron filings, and hence concluded that such a wire must be regarded as a magnet. Two years later Davy showed that the apparent attraction was due to the fact that the particles of iron became magnets under the influence of the current, and that on account of the mutual attractions of the opposite poles they formed chains about the wire.

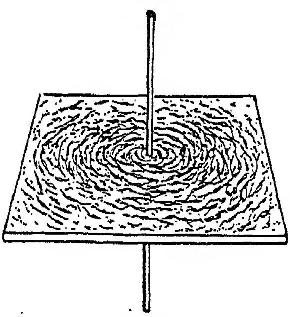


FIG. 613.—The presence of a magnetic field about a wire carrying an electric current shown by action on iron filings.

The action of the current on iron filings and on a magnetic needle may be shown by the following experiments.

Experiments. 1. Arrange a heavy copper wire to pass vertically up through a hole in a card, and sprinkle iron filings a muslin bag the card. Now

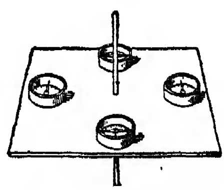


FIG. 614.—The presence of a magnetic field about a wire carrying an electric current shown by the action on a compass-needle.

while a strong current is passing in the wire. Observe that the filings arrange themselves in concentric rings about the wire (Fig. 613).

2. Next, place a small jeweller's compass on the card, and move it from point to point about the wire. Observe the direction of the needle at each place. It will be seen to set itself with its axis tangent to a circle having the wire at its centre (Fig. 614). Reverse the direction of the current and notice that the direction in which the needle points is also reversed.

These experiments show that a **wire through which an electric current is flowing is surrounded by a magnetic field, the lines of force of which form circles around it.** Thus the wire throughout its entire length is surrounded by what has been called a magnetic whirl.

The direction in which a pole of the magnetic needle tends to turn depends on the direction of the current in the wire. Several rules for remembering the relation between the direction of the current and the behaviour of the needle have been given, two of them being as follows:—

1. **Swimmer Rule.** Imagine yourself swimming in the wire with the current and facing the needle; then the N-pole of the needle will be deflected towards your left hand. (See § 506).

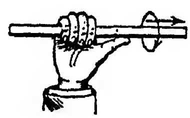


Fig. 615.—Direction of lines of force about a conductor.

2. **Right Hand Rule.** Suppose the right hand to grasp the wire carrying the current (Fig. 615) so that the thumb points in the direction of its flow; then the N-pole will be urged in the direction in which the fingers point.

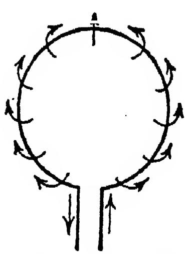


Fig. 616.—Lines of force about a circular loop.

542. Magnetic Field about a Circular Conductor. Since the lines of force encircle a conductor, it would appear that a wire in the form of a circular loop carrying a current (Fig. 616) should act as a disc of steel magnetized so as to have one face a *N*-pole, the other a *S*-pole. That such is the case can be demonstrated in the following way.

Experiment. Take a piece of copper wire and bend it into the form shown in Fig. 617, making the circle C about 20 cm. in diameter. Suspend the wire by a fine thread T and allow its ends to dip into mercury held in receptacles R, R supported upon standards S, S. Pass a current through the circular conductor by connecting the terminals at the foot of the standards to a storage battery with a small resistance in series with the battery.

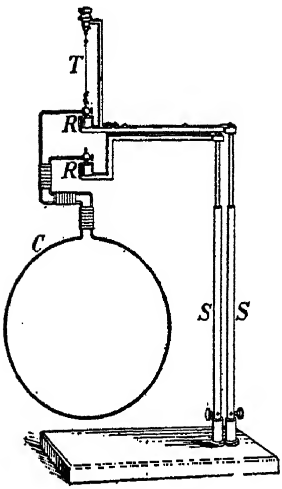


FIG. 617.—Experiment to show that a circular loop carrying a current behaves as a disc magnet.

Now bring a bar-magnet near the face of the loop, and observe that the latter is attracted or repelled by its poles, and behaves in every way as if it were a flat magnetic disc with poles at its faces. Indeed, if the current is strong, and the ends of the wire move freely in the mercury, the loop will set itself with its faces north and south under the influence of the earth's magnetic field.

In taking this position it obeys the general law, that a magnet when placed in the field of force of another magnet always tends to set itself in such a position that the line joining its poles will be parallel to the lines of force of the field in which it is placed.

To fulfil this condition the plane of the coil must become perpendicular to the direction of the lines of force of the field.

A coil carrying a current always tends to set itself in the position in which the maximum number of lines of force will pass through it.

543. Magnet and Floating Coil. The relations between magnetic lines of force and a conductor carrying an electric current are very important and it will be well to illustrate them further. This may be done by means of a magnet and a coil carrying a current and floating on water.

Experiment. A convenient apparatus is shown in Fig. 618. A rectangular coil C, consisting of several turns of cotton-covered wire is supported on a cork float F, from the bottom of which a small flashlight battery B is suspended. Connections between the ends of the coil and the leads L_1, L_2, from the battery are made by spring clips S_1, S_2.

On account of the low voltage in the circuit it is essential that all electrical connections be very secure.

Float the apparatus in a dish of water and anchor it by a thread to a lead sinker. Close the electrical circuit and bring up a bar magnet *M* to one side of the coil with the magnet parallel to the plane of the coil. (Consider the magnet and the coil to be in the plane of the diagram.) Observe now that the coil rotates around a vertical axis such as would be produced by a force acting on the conductors nearest the magnet in a direction perpendicular to the plane of the drawing. If the *S*-pole of the magnet is presented to the coil and the current in the near-by conductors is upward, the force moving the side of the coil

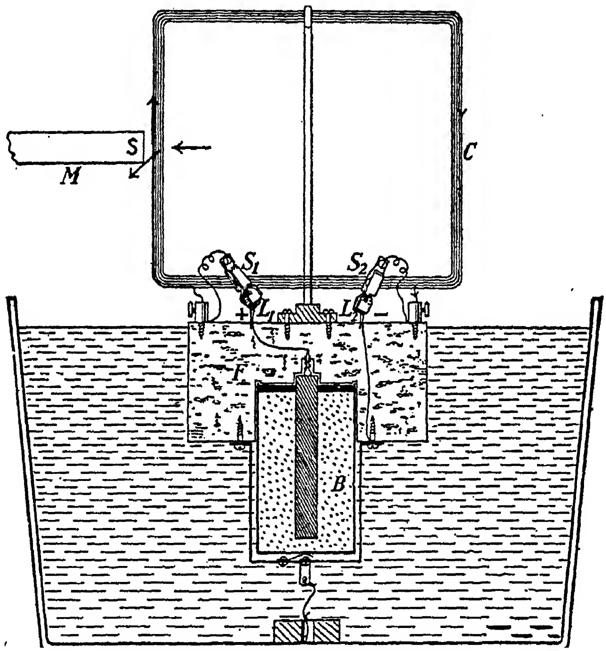


FIG. 618.—A magnet and a floating coil.

near the magnet will be towards the observer, as shown. If either the direction of the current or the polarity of the magnet is reversed the direction of the force is reversed.

Now remembering that the lines of force of a magnet are considered to leave the *N*-pole, pass through the surrounding medium, and enter the *S*-pole (§ 460), we see that the direc-

tion of the current, of the magnetic lines of force, and of the force tending to move the conductor are mutually at right angles. Their relative directions are conveniently represented in Fig. 619. Hold the thumb, first finger and second finger of the right hand at right angles as illustrated. Then if the thumb indicates the direction of the current, and the first finger indicates the direction of the magnetic lines of force, the second finger indicates the direction of motion of the conductor.

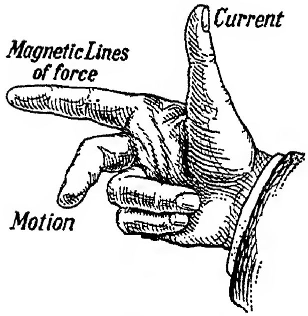


Fig. 619.—Right hand rule for action of a magnetic field on a current of electricity.

544. Magnetic Conditions of a Helix. Ampère showed that the magnetic power of a wire carrying a current could be intensified by winding it into the form of a spiral. The magnetic properties of such a coil can be demonstrated by simple experiments.

Experiments. Make a helix, or coil of wire, about three inches long, by winding insulated copper wire (No. 16 or 18) about a lead-pencil. Connect the ends of the wire with the poles of a dry cell, and with a magnetic needle explore the region surrounding it.

Next, make a helix somewhat larger in diameter, say about three-quarters of an inch, and place it in a rectangular opening made in a sheet of cardboard (Fig. 620). This can be done by cutting out two sides and an end of a rectangle of the proper size and then passing the free end of the strip lengthwise through the helix, and replacing the strip in position. Sprinkle iron filings from a muslin bag on the cardboard around the helix and within it. Attach the ends of the wire to the poles of a battery and gently tap the cardboard.

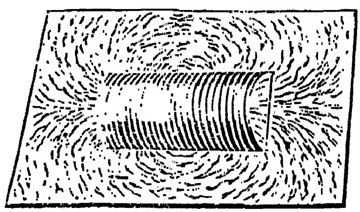


Fig. 620.—A helix carrying a current behaves like a bar-magnet.

In these experiments the helix through which the current is passing behaves exactly like a magnet, having N and S

poles and a neutral equatorial region. The field, as shown by the action of the needle and the iron filings, resembles that of a bar-magnet. (Compare § 459.)

545. Polarity of the Helix and Direction of the Current. There is a fixed relation between the poles of the coil and the direction of the current passing through the wire. If one looks at the south pole of the helix, the electric current passes through the coils in a clock-wise direction (Fig. 621); or, we give a "right hand similar to that in § 541, as follows:—If the helix is gråsped in the right hand, as shown in Fig. 622, with the fingers pointing in the direction in which the current is moving in the coils, the thumb will point to the *N*-pole.

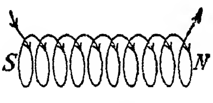


FIG. 621.—Relation of polarity of helix to the direction of the current—clock rule.

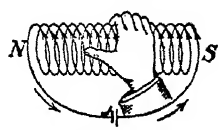


FIG. 622.—Relation of polarity of helix to direction of current — right-hand rule.

546. Electromagnet. Arago and Ampère magnetized steel needles by placing them within a coil of wire carrying a current. Sturgeon, in 1825, was the first to show that if a core of soft-iron is introduced into such a coil (Fig. 623), the magnetic effect is increased, and that the core loses its magnetism when the circuit is opened. The combination of the helix of insulated wire and a soft-iron core is called an **electromagnet.**

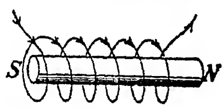
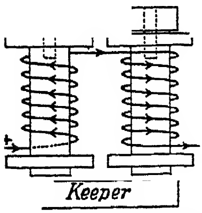


FIG. 623.—The essential parts of an electromagnet.

547. Why an Electromagnet is More Powerful than a Helix without a Core. In a helix without a core the current sets up a magnetizing force which is proportional to the current in the circuit and the number of turns in the helix. When an iron core is inserted in the helix the magnetizing force induces magnetism in it which greatly increases the magnetic effect of the helix. The total magnetic effect set up is often spoken of as the **magnetic flux,** and it may be several hundred times as great as the original magnetizing force.

For best results electromagnets are employed which provide complete paths in iron for the magnetic lines of flux. Such an electromagnet is illustrated in Fig. 624. When the keeper is brought in contact with the pole pieces a very strong pull is exerted on it. With even a small air gap between pole pieces and keeper the pull is much reduced. In the diagram only a few turns of wire in the electromagnet are shown.



[Fig]. 624.—An electromagnet with keeper a slight distance from the pole pieces.

Exercise. Using the rules in § 545 determine the polarity of the magnet in Fig. 624.

548. Powerful Lifting Magnet. An efficient powerful electromagnet is illustrated in Figs. 625, 626. It is constructed so that the paths in the iron for the magnetic flux, as indicated by the broken lines, are short in length and have large area to pass through. The helix for this type of magnet consists of a few turns of wire coiled in the groove in the electromagnet. A small magnetizing field, in a magnet of this type, induces strong magnetism. Such magnets are used for loading and unloading pig iron, iron castings and other heavy pieces of iron inconvenient to handle with ropes or chains. Some magnets have been built capable of lifting 30 tons. The load is released by switching off the current in the coils of the magnet.

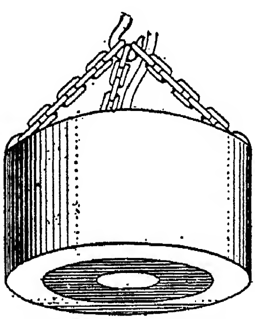


Fig. 625.—Electromagnet for handling heavy iron castings.

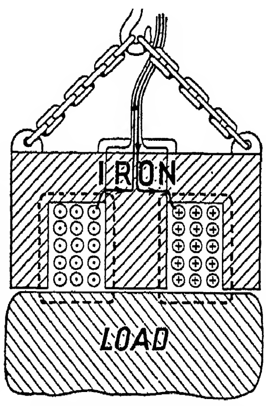


Fig. 626.—Sectional drawing of the electromagnet in Fig. 625.

QUESTIONS

1. Imagine an electric current to be flowing in the direction indicated in each of the loops of wire represented in Fig. 627. Which pole of the coil is at a and which at b in each case?

FIG. 627.—Which side of the loop is N and which S?

2. If n and s represent the poles at the faces of the coils when a current is passed through each loop of wire represented in Fig. 628, in which direction, a or b, is the current flowing in each case?

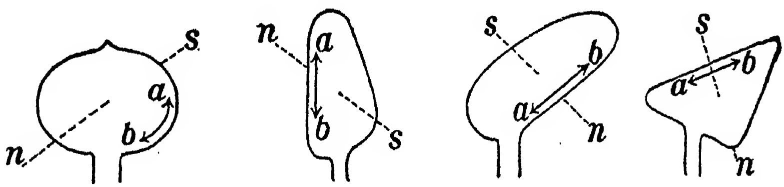


FIG. 628.—In what direction does the current flow?

3. If you were given a voltaic cell, wire with an insulating covering, and a bar of soft-iron, one end of which was marked, state exactly what arrangements you would make in order to magnetize the iron so that the marked end might be an N-pole. Give diagram.

4. A current is flowing through a rigid copper rod. How would you place a small piece of iron wire with respect to it so that the iron may be magnetized in the direction of its length? Assuming the direction of the current, state which end of the wire will be an N-pole.

5. A telegraph wire runs north and south along the magnetic meridian. A magnetic needle free to turn in all directions is placed over the wire. How will this needle act when a current is sent through the wire from south to north? Supposing the wire to run east and west, how would you detect the direction of the current with a magnetic needle?

6. An insulated wire is wound round a wooden cylinder from one end A to the other end B. How would you wind it back from B to A (1) so as to increase, (2) so as to diminish, the magnetic effects which it produces when a current is passed through it? Illustrate your answer by a diagram drawn on the assumption that you are looking at the end B.

7. A small coil is suspended between the poles of a powerful horse-shoe magnet, and a current is made to flow through it. How will the coil behave (1) when its axis is in the line joining the poles of the magnet? (2) when it points at right angles to that line? (Fig. 634.)

8. If it were true that the earth's magnetism is due to currents traversing the earth's surface, show what would be their general direction.

9. An elastic spiral wire hangs so that its lower end just dips into a vessel of mercury. When the top of the spiral is connected with one terminal of a battery, and the mercury with the other, it vibrates, alternately breaking and closing the circuit at the point of contact of the end of the wire and the mercury. Explain this action.

CHAPTER LXXVIII

PRACTICAL APPLICATIONS OF ELECTROMAGNETS

549. Uses of Electromagnets. At the present time electromagnets are employed for a great variety of practical purposes. In most machines where electricity is used, as well as in almost all instruments for making electrical measurements, the electromagnet will be found. The following sections contain descriptions of some of the more common applications.

550. The Electric Telegraph. The electric telegraph in its simplest form is an electromagnet operated at a distance by a battery and connecting wires. The circuit is opened and closed by a **key.** The electromagnet, which gives the signals, is called a **sounder.** When the current in the circuit is not sufficiently strong, on account of the resistance of the line, to work a sounder, a more sensitive electromagnet, called a **relay,** is introduced, which closes a local circuit containing a battery directly connected with the sounder.

551. The Telegraph Key. The key is an instrument for closing and breaking the circuit. Fig. 629 shows its construction. Two platinum contact points *P* are connected with the binding posts *A* and *B*, the lower one being connected by the bolt *C*, which is insulated from the frame, and the upper one being mounted on the lever *L*, which is connected with the binding-post *B* by means of the frame. The key is placed in the circuit by connecting the ends of the wire to the binding-posts.

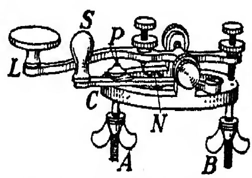


FIG. 629.—Telegraph key.

When the lever is pressed down, the platinum points are brought into contact and the circuit is completed. When the lever is not depressed, a spring *N* keeps the points apart. A switch *S* is used to connect the binding-posts, and close the circuit when the instrument is not in use.

552. The Telegraph Sounder. Fig. 630 shows the construction of the sounder. It consists of an electromagnet *E*, above the poles of which is a soft-iron armature *A*, mounted on a pivoted beam *B*. The beam is raised and the armature held by a spring *S*, above the poles of the magnet at a distance regulated by the screws *C* and *D*. The ends of the wire of the magnet are connected with the binding-posts.

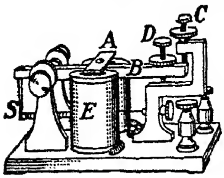


Fig. 630.—Telegraph sounder.

553. The Telegraph Relay. The relay is an instrument for closing automatically a local circuit in an office when the current in the main circuit, on account of the great resistance of the line, is too weak to work the sounder. It is a key worked by an electromagnet instead of by hand. Fig. 631 shows its construction. It consists of a "long coil" electromagnet *R*, in front of the poles of which is a pivoted lever *L* carrying a soft-iron armature, which is held a little distance from the poles by the spring *S*. Platinum contact points *P* are connected with the lever *L* and the screw *C*. The ends of the wire of the electromagnet are connected with the binding-posts *B*, *B*, and the lever *L* and the screw *C* are electrically connected with the binding-posts B_1, B_1.

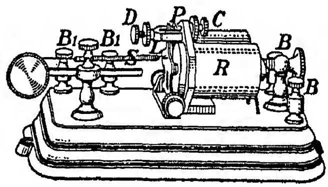


Fig. 631.—Telegraph relay.

Whenever the magnet *R* is magnetized, the armature is drawn toward the poles and the contact points *P* are brought together and the local circuit completed.

554. Connection of Instruments in a Telegraph System. Fig. 632 shows a telegraph line passing through two offices A and B, and indicates how the connections are made in each office.

When the line is not in use, the switch on each key K is closed and the current in the main circuit flows from the positive pole of the main battery at A, across the switches of the keys, and through the electromagnets of the relays R, R to the negative pole of the main battery at B, and thence through the battery to the ground, which forms the return circuit, to the negative pole of the main battery at A. The magnets R, R are magnetized, the local circuits completed by the relays, and the current from each local battery flows through the magnet E of the sounder.

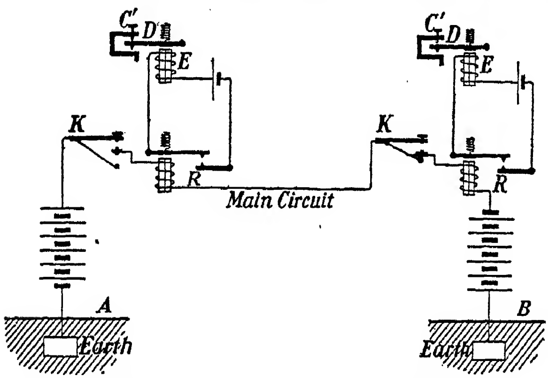


FIG. 632.—Connection of instruments in a telegraph circuit.

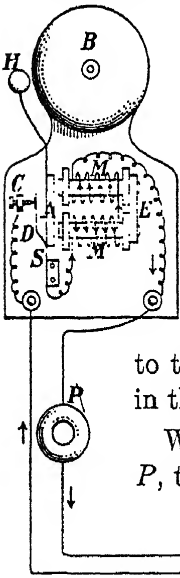
When the line is being used by an operator in any office A, the switch of his key (S in Fig. 629) is opened. The circuit is thus broken and the armature of the relay and of the sounder in each of the offices is released as in the diagram.

When the operator depresses the key and completes the main circuit, the armature of the relay in each office is drawn in, and the local circuit is completed. The screw D of each sounder is then drawn down against the frame, producing a 'click.' When he breaks the circuit at the key, the local circuit is again opened and the beam of each sounder is drawn up by the spring against the screw at C', producing another

'click' of different sound. If the circuit is completed and broken quickly by the operator, the two 'clicks' are very close together, and a "dot" is formed; but if an interval intervenes between the 'clicks', the effect is called a "dash." Different combinations of dots and dashes form different letters. The transmitting operator at A is thus able to make himself understood by the receiving operator at B.

555. The Electric Bell. Electric bells are of various kinds. Fig. 633 shows the construction of one of the most common forms. It consists of an electromagnet M,M,E, in front of the poles of which is supported an armature A by a spring S. At the end of the armature is attached a hammer H, placed in such a position that it will strike a bell B when the armature is drawn to the poles of the magnet. A current breaker, consisting of a platinum-tipped spring D, attached to the armature, is placed in the circuit as shown in the figure.

When the circuit is completed by a push-button P, the current from the battery F passes from the



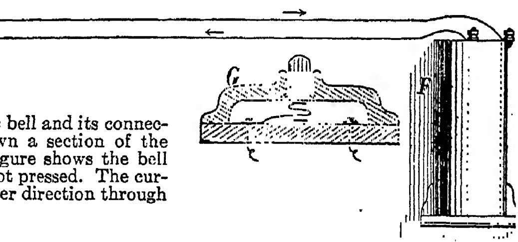


FIG. 633.—Electric bell and its connections. At G is shown a section of the push-button. The figure shows the bell when the button is not pressed. The current may pass in either direction through the electromagnets.

screw C to the spring D and then through the electromagnet to the battery. The armature is drawn in and the bell struck by the hammer; but by the movement of the armature the spring D is separated from the screw C, and the circuit is broken at this point. The magnet then releases

the armature and the spring S pulls it back into its original position, thus completing the circuit again. The action goes on as before and a continuous ringing is thus kept up.

556. Galvanometers. Since the magnetic effect of the current varies as its strength, the strength of different currents may be compared by comparing their magnetic actions. Instruments for this purpose are called **Galvanometers.** There are two main types of the instrument.

In the first type, the strength of the current is measured by the deflection of a magnetic needle within a fixed coil, made to carry the current to be measured; in the second, the strength is measured by the deflection of a movable coil suspended between the poles of a permanent magnet.

The galvanoscope described in § 507 is of the first type.

557. The D'Arsonval Galvanometer. Galvanometers of the second type are generally known as D'Arsonval galvanometers, being named after a French physicist of that name. In such instruments the permanent magnet

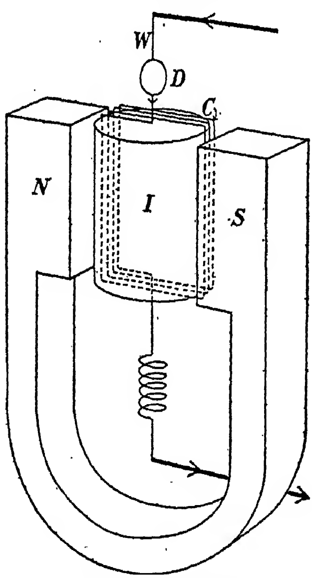


Fig. 634.—Moving coil of galvanometer.

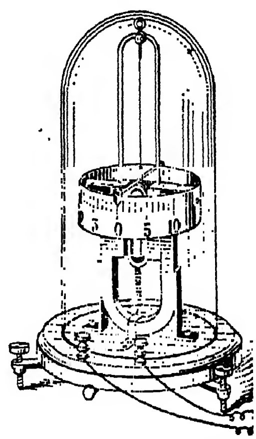


Fig. 635.—A convenient D'Arsonval galvanometer.

remains stationary, and a suspended coil rotates through the action of the current in the field of the permanent magnet. Fig. 634 shows the essential parts of the instrument, and in Fig. 635 a complete instrument is seen. *N* and *S* are the poles of a permanent magnet of the horseshoe type. A cylinder of iron *I* is supported between these poles, leaving a small space on each side between the cylinder and the poles. A light rectangular coil *C* surrounds *I* longitudinally, being suspended by a fine wire *W* so that it is free to move in the magnetic field in the gaps between the cylinder and the poles. The current to be measured enters at the top, passes down *W*, through the coil, through a coiled spring and then leaves the instrument. It causes a rotation of the coil. The deflection of the coil is indicated either by a light pointer and a scale (Fig. 635) or by a mirror *D* attached to the upper part of the coil to reflect a beam of light, which serves as a pointer to indicate the extent of the rotation. (Fig. 634).

The coil is brought to the zero by the torsion of the suspension wires. When the current is passed through it, the coil tends to turn in such a position as to include as many as possible of the lines of force of the field of the permanent magnet, and the deflection is approximately proportional to the strength of the current. Instruments of this type may be made exceedingly sensitive.

558. Ammeter. A galvanometer with a scale graduated to read amperes is called an **ammeter.** The instrument must have a low resistance in order that it may be placed in the circuit without sensibly changing the strength of the current to be measured. (Fig. 636). On account of this low resistance an ammeter should never be connected directly to a storage battery or even to a dry cell in good condition. A suitable resistance must always be in series with it and the cell. Indeed, the function of the ammeter is to measure the

current which the cell sends through this resistance, and if the resistance is not in the circuit, or if it is not great enough, the current which passes through the ammeter may be large enough to ruin it. In all doubtful cases the ammeter should be protected by a piece of fuse wire, as shown in the figure.

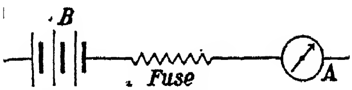


Fig. 636. — Method of inserting an ammeter A to measure the current sent by battery B through resistance R. R may be any electrical instrument or appliance.

The best portable ammeters used for commercial purposes are of the movable coil type and may be considered as modifications of the D'Arsonval galvanometer. Fig. 637 shows an instrument of this class. The coil C, having a stationary soft-iron cylinder within it, is pivoted on jewel bearings between the poles N and S of a permanent magnet of great constancy. It is brought to the zero position by a coil spring sp.

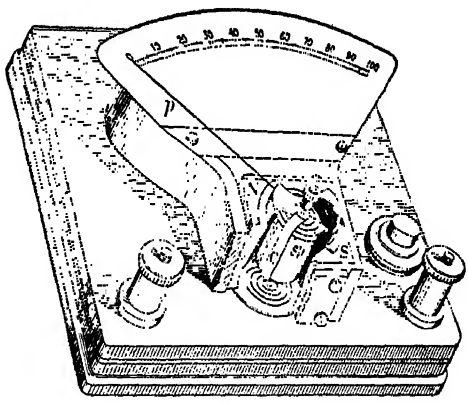


Fig. 637.—Ammeter or voltmeter. C, movable coil; sp, one of the springs; N, S, poles of the permanent magnet; p, pointer.

When the current is passed through the instrument, the coil, to which a pointer p is attached, reacts against the spring and turns about within the field of the magnet.

Each instrument is calibrated by comparison with a standard instrument placed *in series* with it. The method of calibrating a standard ammeter by using a voltameter has been mentioned in § 531.

559. Voltmeter. If the galvanometer is to be used to measure potential differences between points in a circuit, it should have high resistance, in order that the current in the main circuit may not be altered appreciably when the instrument is connected to the two points (Fig. 638). When the scale is graduated to read directly in volts, the instrument is a **voltmeter.**

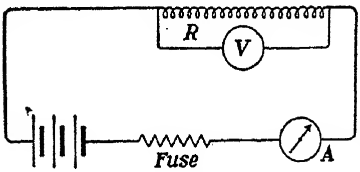


FIG. 638.—The voltmeter *V* is being used to measure the p. d. between the terminals of the resistance *R*. The ammeter *A* registers the current flowing through *R*.

Since the function of a voltmeter is to measure potential difference, and since it has a high resistance it *can* be connected directly to a storage battery or other source of E.M.F., provided that the E.M.F. does not exceed the range of the instrument. Voltmeters are calibrated by being placed *in parallel* with a standard voltmeter.

560. Difference between Ammeter and Voltmeter. The essential difference in construction between the two classes

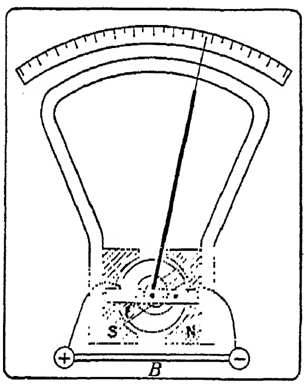


FIG. 639.—The Ammeter.

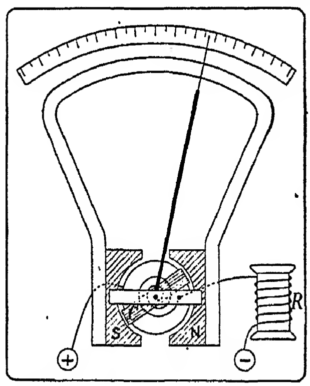


FIG. 640.—The Voltmeter.

of instrument is shown in Figs. 639 and 640. In the ammeter only a small fraction of the current passes through the coil *C*, the main current being carried by the shunt *B*, which has a very low resistance. In the voltmeter the high resistance is

obtained by inserting the resistance coil R in series with the moving coil. In both instruments, then, the current actually passing through the moving coil is small. In Fig. 641 the circuits for a multirange combination volt-ammeter are shown.

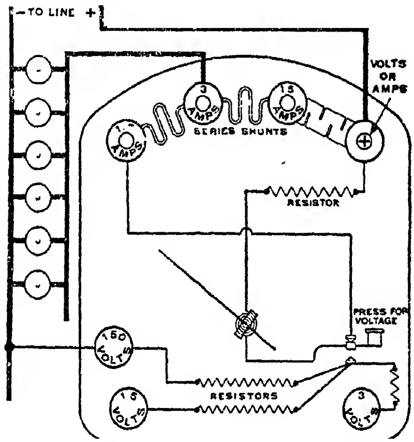


FIG. 641.—Diagram of a Weston D.C. volt-ammeter. This instrument will measure currents up to 15 amperes and potential differences up to 150 volts.

QUESTION

Would the ammeters and voltmeters described in §§ 558, 559 respond to alternating currents? Give reasons. Could alternating current instruments be constructed by substituting coils for the permanent magnets? Make a diagram.

REFERENCE FOR FURTHER INFORMATION

Western Electrical Instrument Co., Newark, N.J., *Lectures on Electrical Apparatus and Experiments.*

CHAPTER LXXIX

ELECTROMAGNETIC INDUCTION

561. Faraday's Experiments. Much of the life of the great investigator Faraday was occupied in endeavours to trace relations between the various "forces of nature"—gravitation, chemical affinity, heat, light, electricity and magnetism. Seeing that magnetic effects could be produced by an electric current, he felt sure that an electric current could be obtained by means of a magnet. During seven years (1824-31), he devoted considerable time to securing experimental proof of this, and at last, in August, 1831, was successful.

562. Production of Induced Currents. Faraday's original experiments are simple and can be performed by anyone without difficulty.

Experiment. Connect the ends of a coil of many turns of insulated wire wound on a hollow spool to a sensitive galvanometer or a zero-centre voltmeter (Fig. 642). Watching the voltmeter closely, thrust quickly a pole of a bar-magnet into the coil; the needle swings to one side and immediately returns to zero. Withdraw the magnet quickly; the needle swings to the other side and then returns to rest. Next, push the coil over one end of the magnet and then remove it. The needle behaves exactly as when the magnet was moved into and out of the coil. In each case the **current in the coil lasts only when the magnet and coil are in motion relative to each other.**

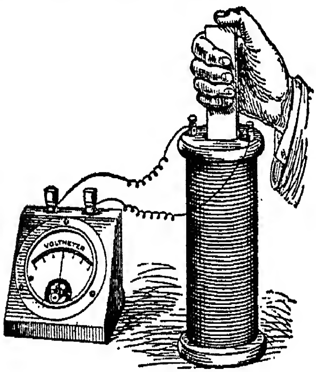


FIG. 642.—Arrangements for studying the production of induced currents. The galvanometer should be far enough from the coil that it will not be affected directly by the magnet.

Now there cannot be a current in a closed circuit unless there is an electromotive force (E.M.F.) in the circuit. Hence we can say that

simply by moving a magnet with its lines of force into and out of a coil there is induced in the coil an E.M.F. If the circuit is closed there will be a current in it, and the greater the resistance of the coil, for a given E.M.F., the smaller will be the current.

As the result of many accurate experiments it has been shown that the magnitude of the induced E.M.F. for any given circuit is proportional to the rate of change of the magnetic flux in the circuit.

Faraday's discoveries may be summed up in the following statement: **Whenever for any cause a conductor cuts, or is cut by lines of magnetic flux, an electromotive force is induced in the conductor, the magnitude of which is proportional to the rate of change of the magnetic flux relative to the conductor.**

563. Direction of the Induced Currents: Lenz's Law. The direction in which the induced current flows should be investigated experimentally and it may be carried out with apparatus illustrated in Fig. 642 in the last section.

Experiment. First connect a dry cell through a suitable resistance to the voltmeter and note which way the pointer swings when the current enters the instrument by a given terminal. Having done this it will be possible, by observing the direction of the deflection, to say by which terminal the current enters the voltmeter.

Next, disconnect the cell and, having connected the coil again as in Fig. 642, insert the N-pole of a bar magnet into the coil. From the deflection of the voltmeter and the way the coil is wound, trace out the direction in which the induced current must be flowing around the upper face of the coil. It will be found that the direction is anti-clockwise, and that therefore this face of the coil is made an N-pole by the induced current.

On withdrawing the N-pole, the induced current is found to flow in the opposite direction, and hence the upper face of the coil is now made an S-pole by the induced current.

Now since like poles repel, the insertion of the N-pole must have been opposed by the N-pole produced by the induced current; also, since unlike poles attract, the withdrawal of the N-pole was opposed by the S-pole produced by the induced current. Similar results will be obtained by inserting and withdrawing the S-pole of the bar-magnet.

Hence, in all cases of electromagnetic induction, **the direction of the induced current is always such that it produces a magnetic field which opposes the motion or change which induces the current.** This is known as **Lenz's Law.**

564. Demonstration of Lenz's Law. Lenz's law may be applied to explain the operation of various electrical machines and it will be well to demonstrate its principles. The apparatus illustrated in Fig. 643 is suitable for this purpose. An electromagnet M may be rotated rapidly about a horizontal axis by multiplying gears driven by a crank C. For simplicity only a few turns of the coils of the electromagnet are shown. Current from the battery may enter by the binding-post E on the frame of the apparatus, pass through the coils of the electromagnet, leave it by the brush B mounted on a block insulated from the base and then go to the other end of the battery. The brush B rests on a commutator ring A connected with the windings of the electromagnet. Opposite the poles of the electromagnet is a light aluminium disc D mounted on its shaft S parallel to the axis of rotation of the electromagnet. An iron plate F is mounted just behind the disc. When the electromagnet is excited the lines of magnetic flux go out from the N-pole, pass through the aluminium disc approximately at right angles to it, are concentrated in the iron plate through which they pass and then return through the disc to the S-pole of the electromagnet.

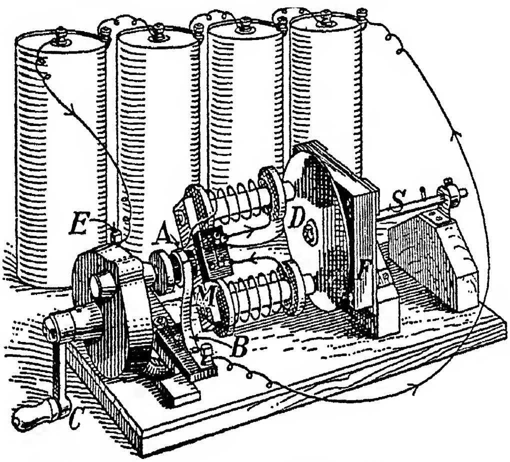


FIG. 643.—Apparatus to demonstrate Lenz's Law.

First, let the electromagnet be fixed in position and not excited, *i.e.*, with no current passing through its coils, and rotate the disc. It turns easily. Now switch on the current and turn the disc. It turns with some difficulty, and the faster it turns the greater is the resistance to its motion. Switch off the current and it spins about freely again.

The resistance to the turning of the disc is due to the action of the lines of magnetic force which pass through it. The disc moves relative

to the lines of force and E.M.F.'s proportional to the speed of rotation are induced in the disc. The disc may be looked upon as composed of various paths for the current to pass through. Even though the induced E.M.F. is small, the resistance of the paths for the current is very small and the corresponding induced currents are large. In accordance with Lenz's law the currents flow in directions which produce magnetic fields opposing the motion.

Second, rotate the electromagnet. If it is not excited there is no effect on the aluminium disc, but as soon as the current is switched on, the disc begins to rotate. The lines of magnetic force sweep through the disc and the currents induced in it produce a magnetic field which is attracted by the poles of the electromagnet. The result is the disc is "dragged" around and the action is sometimes called a magnetic drag. If now a spiral spring is attached to the shaft of the disc in such a way that as the disc turns the spring is uncoiled (or coiled up), it will be found that the torsional force of the spring increases with the speed of rotation of the magnetic field—the faster the rotation, the greater is the angle through which the disc is "dragged".

565. Automobile Speedometer. One type of speed indicator is an application of the "magnetic drag" just described. A small permanent magnet is mounted so that it can be made to rotate by means of gears and a flexible shaft connected with the transmission shaft of the motor car, so that the speed of rotation of the magnet is proportional to that of the engine and hence of the car. Very near the magnet is a disc which can rotate on its own shaft and to this shaft is attached a spiral spring. The faster the car moves the greater is the angle through which the disc is "dragged". A pointer connected to the disc may be used to move about a dial graduated in miles per hour. Another type of speedometer is referred to in § 575.

566. Primary and Secondary Currents. If an electromagnet (Fig. 644) is used in place of the bar magnet in the preceding experiments, similar results will be obtained.

Again, if an electromagnet is allowed to rest within the coil and the battery circuit is quickly broken or closed by a key, an induced current will be produced in the coil each time the circuit is broken or closed. This is what we should expect, since breaking the circuit is equivalent to withdrawing the electromagnet, while making the circuit is the same as inserting the electromagnet.

The coil connected with the battery is called the **primary coil,** and the current which flows through it is **called the primary current;** the coil connected with the galvanometer

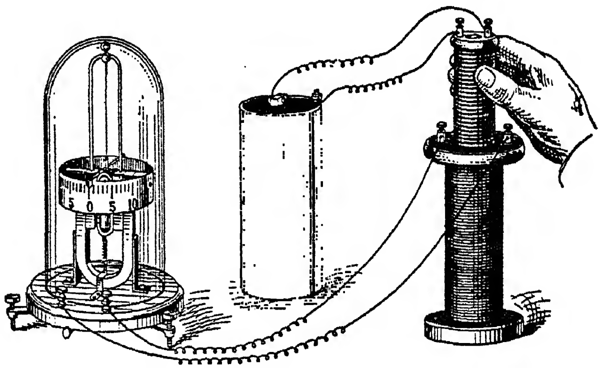


FIG. 644.—Apparatus for illustrating primary and secondary currents. The galvanometer may be replaced by the voltmeter shown in Fig. 642.

is called the **secondary coil,** and the momentary currents made to flow in it, **secondary currents.**

567. Relative Directions of Primary and Secondary Currents. If the experiment of making and breaking the current in the electromagnet described in the preceding section is repeated and care taken to trace the directions of the currents in the primary and secondary coils, it will be found that whenever a **decrease** in the number of lines of force which pass through the secondary coil takes place, the secondary current flows in the **same direction** as the primary current, but that whenever an **increase** in the number of lines of force takes place, the secondary current is **opposite in direction** to the primary current.

Exercise. Show by diagrams that the relations just stated between the directions of the primary and secondary currents can be deduced directly from Lenz's Law.

568. Self-Induction. If an electromagnet containing many turns of wire is connected with a battery and the circuit is closed and opened by touching the two ends of the connecting

wires together and then separating them, a spark will be observed at the ends of the wires when they are separated, and if the hands are in contact with the bare wires, a shock will possibly be felt.

The effects observed are due to what is known as **self-induction** or **inductance.**

569. High E.M.F. and Self-induction. The production of high E.M.F. by self-induction can be demonstrated by means of a circuit represented in Fig. 645. A battery B is connected through a switch, or preferably a mercury press-key K, to a coil with large inductance. A strong electromagnet or the 110-volt circuit of a small transformer is suitable for this purpose. One or more neon bulbs N joined in series are connected across K and a condenser C of large capacity also connected in parallel with K, as shown in the diagram. A switch S permits the condenser to be placed in or cut out of the circuit.

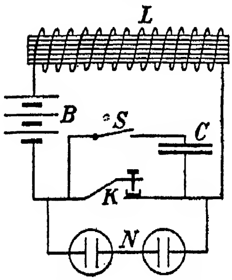


FIG. 645. — Arrangement for the study of self-induction.

(1). With the condenser out of the circuit. Press K. The current passes through the coils of L and it becomes an electromagnet with its magnetic lines surrounding it. Now break the circuit by releasing K. A spark occurs at the mercury surface and a discharge passes through the bulbs. This shows that when the circuit is broken a high E.M.F. is produced.

(2). Close the switch S, placing C in the circuit. Press K and then release it. The spark at K is much weaker. This is due to the fact that a large part of the current surge, which gives rise to the spark at the break in the circuit, is absorbed temporarily by the condenser and is then sent back in the reverse direction through the circuit.

570. Extra Current. We have seen that, in the case of two distinct coils of wire near each other, when a current is started or stopped in one, a current is induced in the other. This is due to the fact that the number of magnetic lines of force passing through the second coil is thereby altered. But we can have this inductive effect with a single coil. When the current is broken the magnetic field accompanying it begins to collapse and the withdrawal of this field of force

from the coil sets up a self-induced current which, in accordance with Lenz's law, opposes the withdrawal of the field. In other words, the current tends to keep on flowing, like a car which continues to run for some time after the power which drives it is shut off.

On completing the circuit, a magnetic field is introduced into the coil and the introduction of this field produces an induced current in the coil which opposes the oncoming current. This action is similar to the inertia of a car when it is started; it takes some time for the car to acquire its maximum speed. Indeed, self-induction may be considered as **electromagnetic inertia.**

The direct induced current in the primary wire itself, which tends to maintain the current when the circuit is broken, is called the **extra current.**

571. The Induction Coil.* In the induction coil currents of very high electromotive force are produced by the inductive action of an interrupted current. (Fig. 646.)

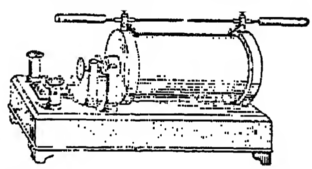


Fig. 646.—The induction coil.

The essential parts of the instrument are shown in Fig. 647. The primary coil consists of a few turns of stout insulated wire wound about a soft-iron core. The secondary coil, consisting of a great number of turns of very fine insulated wire, surrounds the primary coil. Its terminals are attached to binding-posts placed above the coil. The current-breaker is usually of the type illustrated in the electric bell (§ 555), but other forms of interrupters are often employed. The

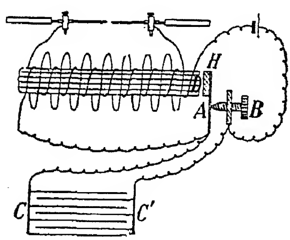


Fig. 647.—The essential parts and electrical connections in the induction coil.

*The induction coil was greatly improved by Ruhmkorff (1803-1877), a famous manufacturer of scientific apparatus in Paris, and is often called the Ruhmkorff coil.

condenser $C\ C'$ is made up of alternate layers of tinfoil and paraffined paper or mica, connected with the spring A and the screw B of the current-breaker in such a way that one of these is joined to the even sheets of the foil and the other to the odd ones. The core is a bundle of soft-iron wires insulated from one another by shellac. Such a core can be magnetized and demagnetized more easily than one of solid iron.

572. Explanation of the Action of the Coil. When the primary circuit is completed, the battery current passes through the coil and magnetizes the core. This draws in the hammer H, and the circuit is broken between the spring A and the screw B. The hammer then flies back, the circuit is again completed and the action is repeated. An interrupted current is thus sent through the primary coil, which induces currents of high electromotive force in the secondary.

While the current is building up in the primary coil the E.M.F. induced in the secondary acts to send the current therein, in a direction opposite to that of the primary current. The secondary E.M.F. is said to be **inverse.** On the break of the primary circuit the directions are the same for both circuits and the secondary E.M.F. is said to be **direct.** In actual use however the induced E.M.F. is so much greater on the break than on the make that the coil is usually effective only on the break.

Experiment. This effect can be easily demonstrated by the following experiment. Connect the primary of an ignition coil C (or other induction coil) in series with a dry cell B and a key K. Insert a wedge in front of the vibrator V so as to stop the operation of the automatic make and break. Connect two or three neon bulbs N in series with the secondary terminals of the coil and observe the effect when the primary circuit is made and broken by means of the key. With a suitable adjustment of the circuits a discharge is obtained in the neon bulbs only on the break of the primary circuit. Again if the coil is used with the automatic make and break, only one side of each neon lamp lights up.

The fact that the E.M.F. is greater on the break indicates that the primary current breaks down more quickly than it builds up. Neither

operation is instantaneous because the self-induction of the primary opposes the change in both cases. On the break of the primary circuit, however, extra resistance is introduced into the circuit because of the gap formed between the contact points. This quickly retards the flow of current which the action of self-induction tends to maintain in the primary circuit, making the break much sharper than the make.

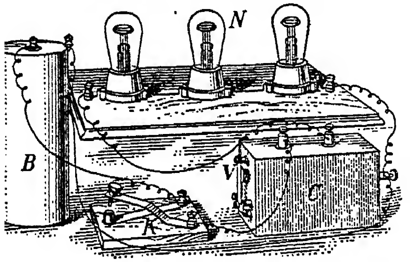


Fig. 648.—Apparatus to show that the E.M.F. induced in the secondary is greater on the break than on the make of the primary.

The rapidity of the break down of the primary current is still further increased by the action of the condenser connected in parallel with the contact points. The current surge tending to pass across the gap passes into the condenser and is then returned to the primary circuit in the reverse direction. This destroys any residual magnetism retained by the core, giving a very rapid break of the primary current.

Exercise. Examine the ignition system of an automobile or a motor-boat. Observe how the current from the battery is made and broken in the primary circuit; and how the high-tension secondary current is distributed to the spark-plugs.

Discuss the importance in this system of the fact that the secondary current is greater on the break than on the make of the primary circuit. Why is an ignition system inefficient without a condenser?

QUESTIONS

1. You have a metal hoop. By means of a diagram describe some arrangement by which, without touching the hoop, you can make electric currents pass around it, first one way, and then the other.

2. A coil about one foot in diameter, made of 400 or 500 turns of fine insulated wire, is connected with a sensitive galvanometer. When it is held with its plane facing north and south, and then turned over quickly, the needle of the galvanometer is disturbed. Give the reason for this.

3. A bar of perfectly soft iron is thrust into the interior of a coil of wire whose terminals are connected with a galvanometer. An induced current is observed. Could the coil and bar be placed in such a position that the above action might nearly or entirely disappear? Explain fully.

4. Around the outside of a deep cylindrical jar are coiled two separate pieces of fine silk-covered wire, each consisting of many turns. The ends

of one coil are joined to a battery, those of the other to a sensitive galvanometer. When an iron bar is thrust into the jar, a momentary current is observed in the galvanometer coils, and when it is drawn out, another momentary current (but in an opposite direction) is observed. Account for these results.

5. A small battery was joined in circuit with a coil of fine wire and a galvanometer, in which the current was found to produce a steady but small deflection. An unmagnetized iron bar was now plunged into the hollow of the coil and then withdrawn. The galvanometer needle was observed to recede momentarily from its first position, then to return and to swing beyond it with a wider arc than before, and finally to settle down to its original deflection. Explain these actions, and state what was the source of the energy that moved the needle.

6. A copper ball is suspended on a thread between the poles of an electromagnet and turned round by hand thus twisting the thread. It is then set free. Describe the behaviour of the ball when the current is turned on and off.

7. The poles of a voltaic battery are connected with two mercury cups. These cups are connected successively by:—(1) A long straight wire. (2) The same wire arranged in a close spiral, the wire being covered with some insulating material. (3) The same wire coiled around a soft-iron core. Describe and discuss what happens in each case when the circuit is broken.

REFERENCES FOR FURTHER INFORMATION

Hadley, *Magnetism and Electricity for Students*, Chapter 22.
Hutchinson, *Magnetism and Electricity*, Chapter 17.

CHAPTER LXXX

DYNAMOS AND MOTORS

573. The Principle of the Dynamo. In its simplest form, a dynamo is a coil of wire rotated about an axis in a magnetic field. For simplicity let us consider a coil consisting of a single turn of wire with its two ends joined to two rings, which allow the coil to rotate freely. On each ring rests a brush, and a wire joining the brushes carries any

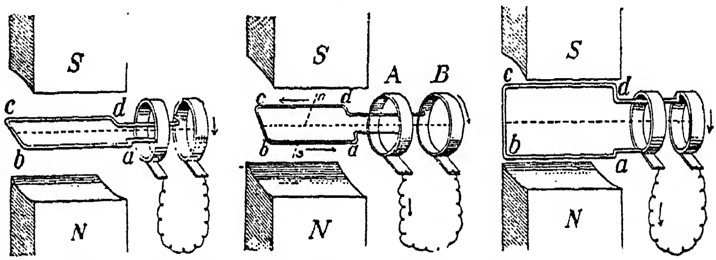


FIG. 649.—Showing what takes place in the first quarter of a rotation.

current which may be produced in the coil. Remember that the lines of force run from N-pole across the air-space to S-pole.

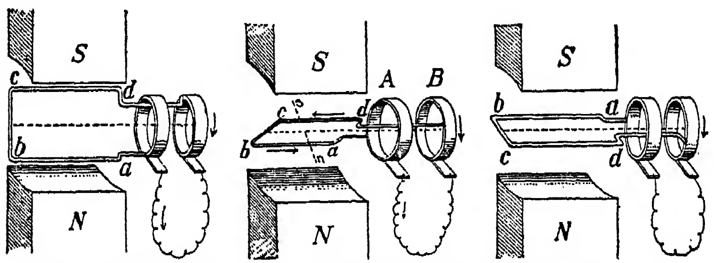


FIG. 650.—Production of a current during the second quarter of a rotation.

As the coil rotates about its axis from the first position shown in Fig. 649, the number of the lines of force passing through the coil will be decreasing during the first quarter turn (Fig. 649), increasing during the second quarter turn,

(Fig. 650), decreasing during the third quarter turn (Fig. 651), and again increasing during the fourth quarter turn (Fig. 652).

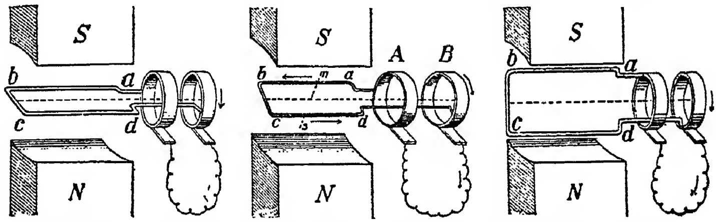


FIG. 651.—Production of a current during the third quarter of a rotation.

The number of lines of force which cut the coil is accordingly always increasing or decreasing as the coil is revolved between the poles of the magnet. The revolution of the

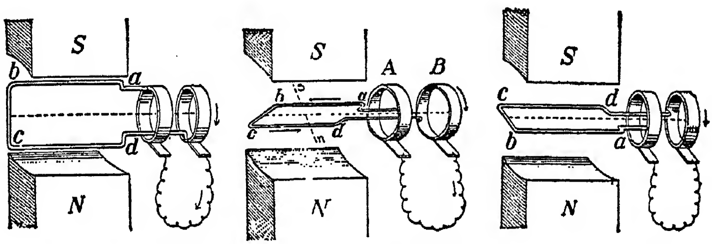


FIG. 652.—Production of a current during the fourth quarter of a rotation.

coil is, therefore, accompanied by the development of induced currents within the circuit.

In what direction do these induced currents flow? In obedience to Lenz's Law (§ 563) the magnetic fields produced by the induced currents as the coil revolves upon its axis must be such as to oppose the rotation of the coil. But we have learned that a loop of wire carrying a current behaves very much like a magnetized steel disc with its opposite faces as N and S poles (§ 542). Then if N and S represent the poles of the permanent fields, and n and s the poles of the fields produced by the induced currents set up by the revolution of the coil, the n and s poles must be distributed in each position in the rotation in such a way that the motion is opposed by the attractions of the N and s poles and of the S

and n poles, and by the repulsions of the N and n poles and of the S and s poles. To meet these conditions, in each of the quarter turns of the revolution, the poles must be distributed as shown for the first quarter turn by the dotted lines in Fig. 649; for the second quarter turn in Fig. 650; for the third quarter turn in Fig. 651; and for the fourth quarter turn in Fig. 652.

But in order to produce such fields the induced currents must flow in the directions shown by the arrows in the figures. (§ 545). That is to say, during the first half turn (Figs. 649, 650) the currents must flow in the direction *d c b a* and during the next half turn (Figs. 651, 652) in the direction *a b c d*. Because of the reversal in the direction of flow the currents are said to be alternating.

574. The Armature of the Dynamo. We have, for simplicity, considered in the preceding section the case of the revolution of a single turn within the magnetic field. In ordinary practice a number of turns are connected to the same collecting rings or plates. These turns are wound about a soft-iron core, which serves to hold them in place and to increase the number of lines of force passing through the space inclosed by them. The coils and core with the attached connections constitute the **armature** of the dynamo.

The armatures vary in type with the form of the core and the winding of the coils. A single coil wound in a groove about a soft-iron cylinder (Fig. 653) forms a **shuttle** armature; when a number of coils are similarly wound about the same iron cylinder the armature is said to be of the **drum** type.

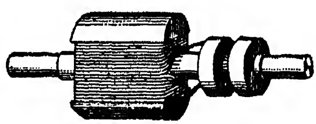


FIG. 653.—Shuttle armature.

In Fig. 654 is shown a drum armature with numerous coils, each containing several turns of wire fitted into grooves cut in the iron core parallel with the shaft. To prevent the

generation of "eddy currents," within the iron itself, which are wasteful of energy and overheat the machine, the armature core is built up of thin discs insulated from one another.

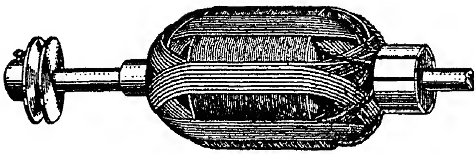


FIG. 654.—Ordinary drum armature.

575. Field Magnets. In small generators, used to develop high tension (or high potential) currents, permanent magnets are sometimes used to produce the fields. The machine is then called a **magneto.** Magnetos are used in rural and portable telephones for calling the distant station, and in gas-engines for ignition. A telephone magneto is shown diagrammatically in Fig. 655 while its general appearance is represented in Fig. 656. It generates an alternating E.M.F., as can be proved by connecting a neon bulb to its terminals. The bulb lights up intermittently, first on one side and then on the other, thus showing an alternating current in the circuit. In all ordinary dynamos the field is furnished by electromagnets known technically as **field-magnets.** These magnets are either bipolar (Fig. 661) or multipolar (Fig. 657). In the multipolar type two or more pairs of poles are arranged in a ring about a circular yoke.

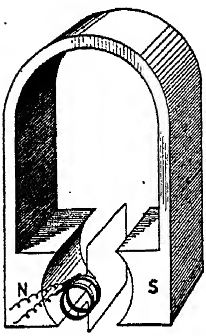


FIG. 655.—Principle of the telephone magneto.

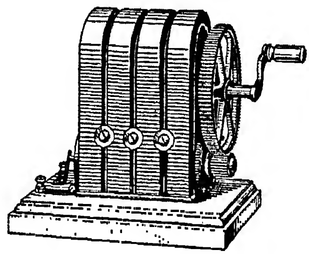


FIG. 656.—Appearance of the telephone magneto. The small gear-wheel is on the end of the armature shaft.

Magneto Speedometer. The potential difference between the terminals of a magneto is directly proportional to the revolutions per minute of the armature, and this fact provides a principle for a speedometer. A magneto

is geared to the transmission shaft of the motor car, and wires run from its terminals to a voltmeter which, instead of showing volts, is graduated in miles per hour.

576. The Alternating Current Dynamo. When an alternating current is used for electric lighting or power transmission, the complete alternations* or cycles range from 25 to 60 per second. Now such a current cannot be generated in a bipolar field except by unduly increasing the rapidity of the revolutions of the armature, because only one cycle is produced for each revolution of the armature. The requisite number of cycles is secured by increasing the number of pole-pieces in the field-magnets. In the alternators in common use, the armature coils A, A . . . (Fig. 657) revolve in a multipolar field. They are wound alternately in opposite directions and connected in series, and the two free ends of the wire are brought to two collecting rings, C and D, as shown in the figure.

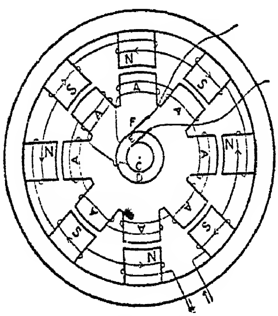
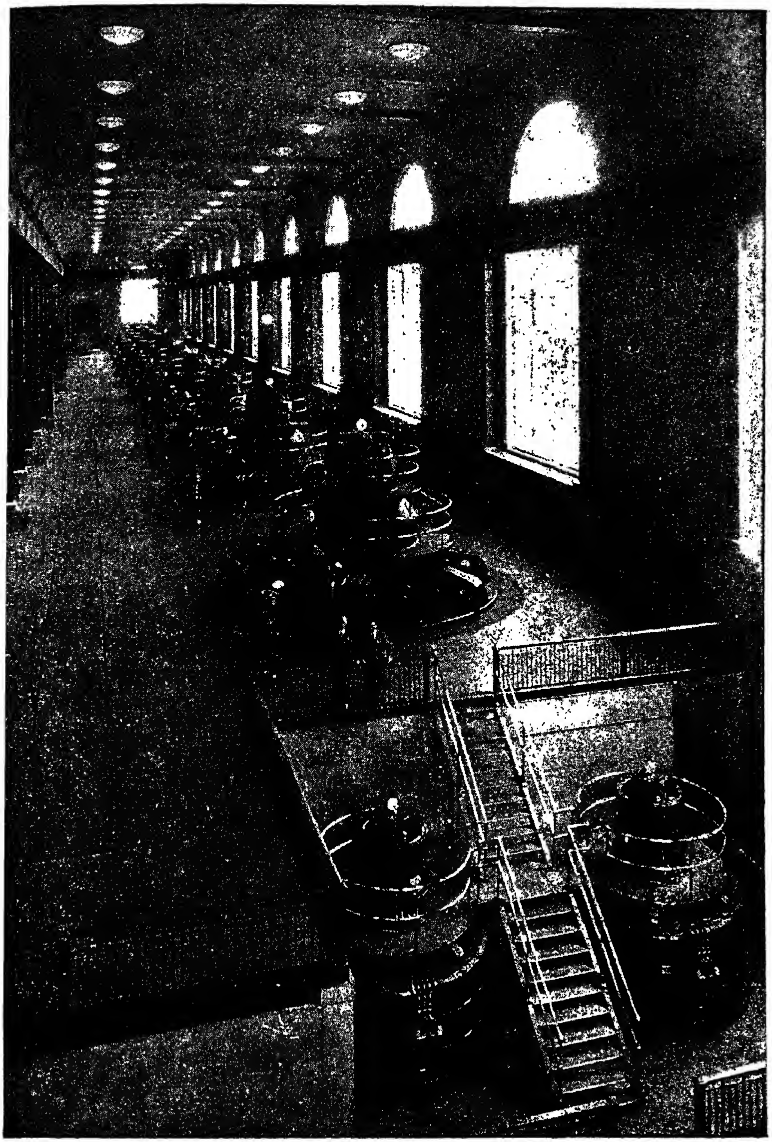


FIG. 657.—Essential parts and electrical connections in the alternating current dynamo.

To study the action, suppose the ring of armature coils to be opposite to the ring of field coils, and to be revolving in either direction. Since the armature coils leaving positions opposite N-poles in the field have currents induced in them opposite in direction to those in the coils leaving S-poles, and since these coils are wound alternately to the right and the left, it is evident that the induced current in each coil will be in such a direction as to produce a continuous current in the whole series, which will flow from one collecting ring to the other. It is evident, also, that the direction of this current will be reversed the instant the field and armature coils again face each other.

*By a complete alternation or cycle is meant a motion of the current forwards and backwards.



THE GENERATORS IN THE QUEENSTON POWER HOUSE OF THE HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO

Each generator is directly above the turbine water wheel which drives it. The turbines are rated at 60,000 h.p. and each generator delivers 2,165 amperes at 12,000 volts. The two smaller machines in the foreground are service generators for the operation of the plant equipment.

(Photograph from the H.E.P.C. of Ontario) **Plate 31**

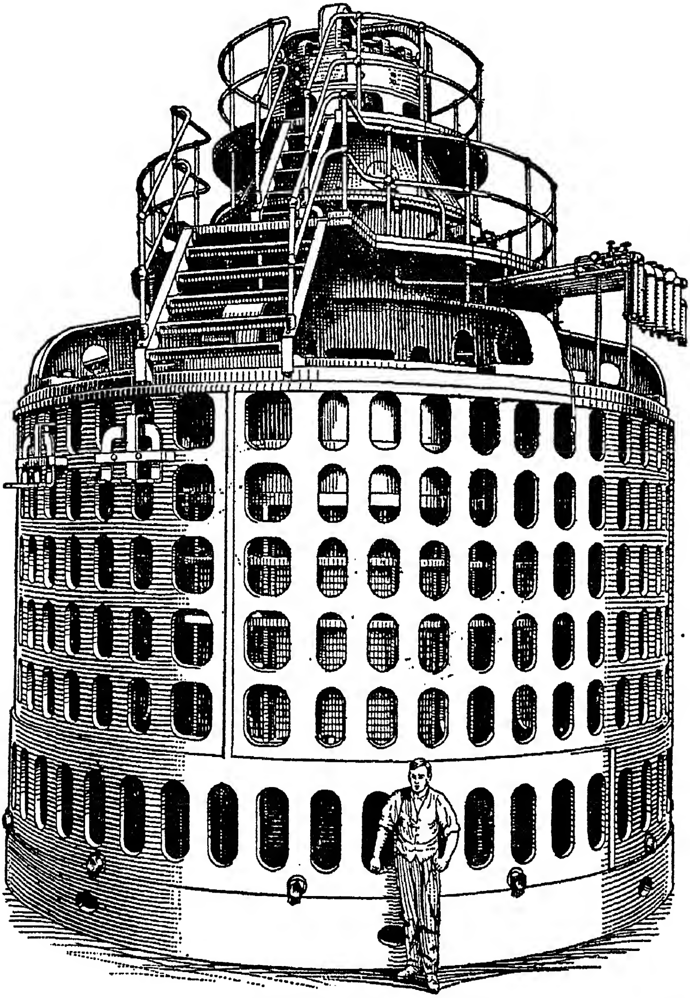


FIG. 658.—One of the ten great generators of the Hydro-Electric Power Commission of Ontario at Queenston (see § 87). The complete generator is 24½ ft. in diameter, 30½ ft. in height and weighs 690 tons. In these machines the field-magnets rotate while the armature remains stationary. The rotor, or moving part, weighs 308 tons and rotates 187½ times per minute. The output is 45,000 kw. The current is generated at 12,000 volts, 25 cycles per second. The generators were built by the Canadian Westinghouse Co. at Hamilton and the Canadian General Electric Co. at Peterborough, Ont.

Since the number of single alternations of this current for each revolution of the armature equals the number of poles in the field-magnet, the number of single alternations

second is equal to the number of poles in the field-magnet multiplied by the number of revolutions made by the armature per second. The number of complete alternations or cycles will be one-half this number.

577. Production of a Direct Current—The Commutator. When an electric current flows continuously in one direction it is said to be a **direct** current. The current in an armature coil changes direction, as we have seen, at regular periods. To produce a direct current with a dynamo it is necessary to provide a device for commuting the alternating into a direct current. This is done by means of a **commutator.** It consists of a collecting ring made of segments called **commutator bars,** insulated from one another. The terminals of the coils are connected in order with the successive bars of the ring. Take, for example, the case of a single coil revolved in a bipolar field, as considered in § 573. The commutator

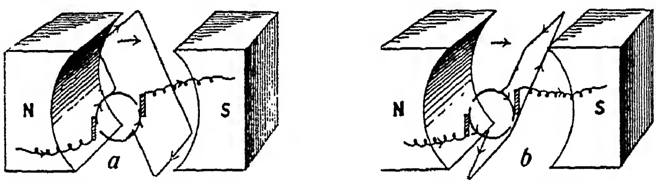
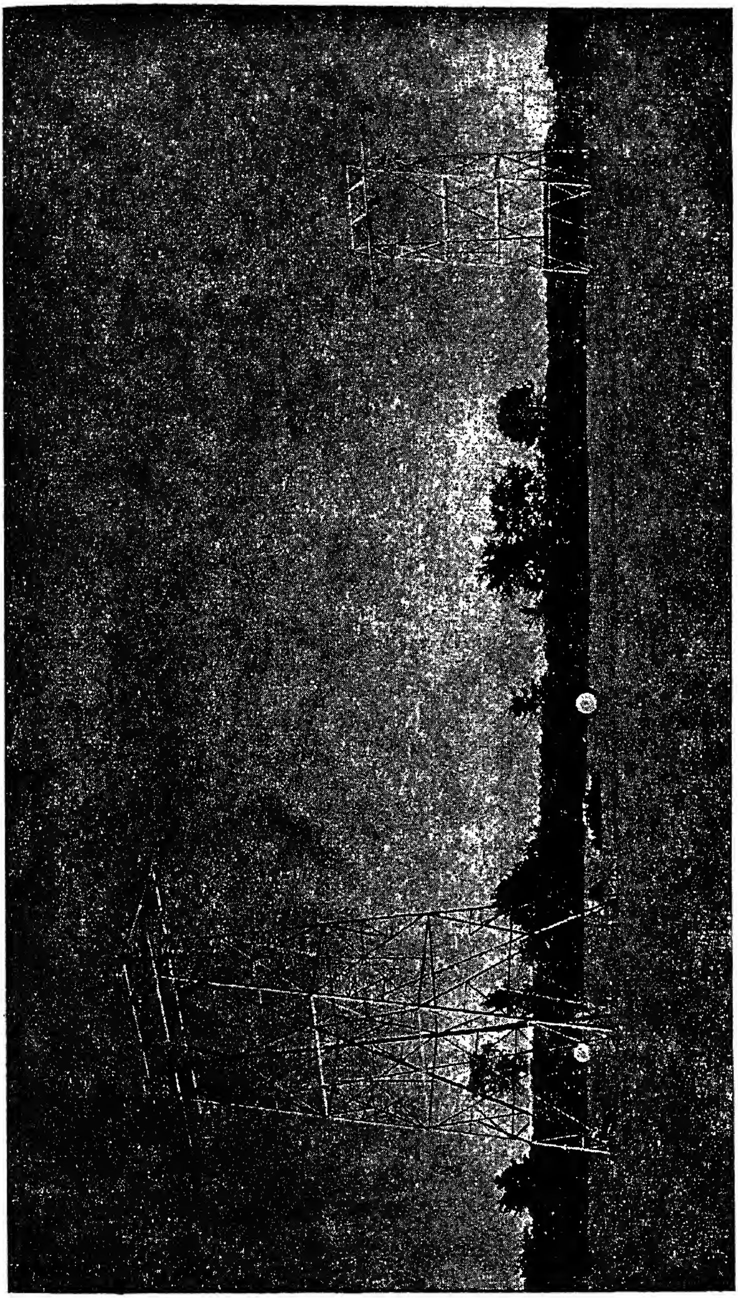


FIG. 659.—Explaining the action of the commutator. While the armature coil moves from its position in *a* to its position in *b* the direction of the current is reversed, but the direction in the external circuit is unchanged.

consists of two semi-circular bars, (Fig. 659), and the brushes are so placed that they rest upon the insulating material between the bars at the instant the current is changing direction in the coil. Then since the commutator bars change position every time the current changes direction in the coil, the current always flows in the same direction from brush to brush in the external circuit.

578. Direct Current Dynamo. The essential parts of a direct current dynamo with shuttle armature and bipolar field are shown in Fig. 660. In this particular dynamo the



No

● Plate 32

● Plate 32

The current is carried by three cables, the phase of the alternations differing in the three conductors. The above view was taken at Cumberland Station in Russell County.

(Photograph from the H.E.P.C. of Ontario)

field-magnets are in series with the armature and the external circuit, and the same current flows through all parts of the circuit. When the armature is rotated in the clockwise direction the induced current leaves the armature by the brush A and passes around the field-magnets in such a direction as to make the right-hand pole-piece an S-pole and the left-hand one an N-pole. It then passes through the external circuit, (consisting, in this case, of two lamps,) and then back to the armature by the brush B.

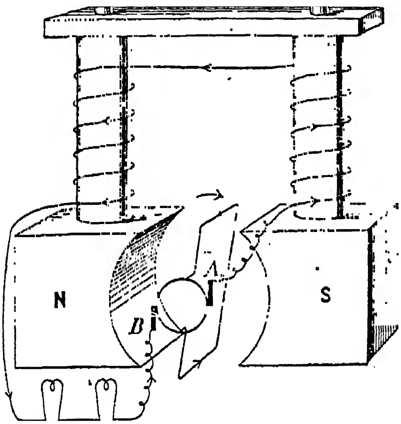


FIG. 660.—Principle of construction of a direct current dynamo.

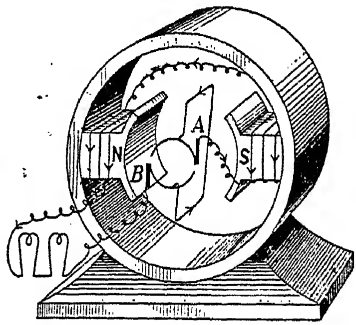


FIG. 661.—A common form of direct current dynamo.

The general plan of connections for a simple circular-shaped dynamo is illustrated in Fig. 661. In the ordinary dynamo, however, the armature windings are complicated and the commutator contains many segments. The windings are imbedded in grooves along a cylin-
core

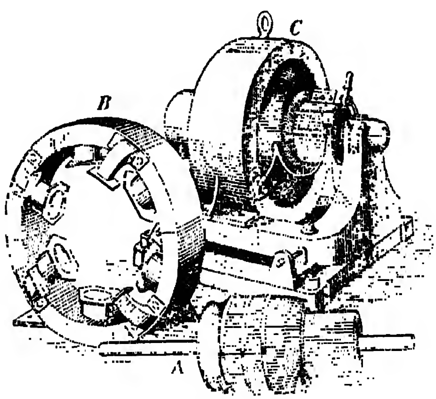


FIG. 662.—Modern direct-current dynamo. A, drum armature. B, multipolar field; C, dynamo complete.

on the shaft and thus an intense magnetic field about the windings is produced. In large dynamos there are several pole-pieces on the outer circular frame, and as many pairs of collecting brushes as there are pairs of poles. In Fig. 662 is shown a modern direct-current dynamo with drum armature and multipolar field. An explanation of the connections between the coils is beyond the scope of this book.

In describing a dynamo, A.C. stands for alternating current, D.C. for direct current.

579. Excitation of the Fields in a Dynamo. In the alternating-current dynamo the electromagnets which form the fields are sometimes excited by a small direct-current dynamo belted to the shaft of the machine. In the great generator shown in Fig. 658 the exciter has a capacity of 150 kw., the voltage being 250. It is mounted above, with its armature on the upper end of the main shaft. In the direct-current dynamo the fields are magnetized by a current taken from the dynamo itself. When the full current generated in the armature (Fig. 663) passes through the field-magnets, which are wound with coarse wire, the dynamo is said to be series-wound. A dynamo of this class is used when a constant current is required, as in arc lighting. When the fields are energized by a small fraction of the current, which passes directly from one brush through many turns of fine wire in the field coils, to the other brush, while the main current does work in the external circuit (Fig. 664), the dynamo is shunt-wound. This type is used where the output of current required is continually changing, but where the potential difference between the brushes must be kept constant, as in incandescent lighting, power distributing, etc. The regulation is accomplished by suitable resistance placed in the shunt circuit to vary the amount of the exciting current.

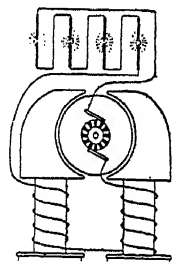


Fig. 663.—Series-wound dynamo.

The regulation is more nearly automatic in the compound-wound dynamo. In this form the fields contain both series and shunt coils.

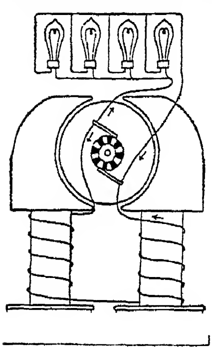


Fig. 664.—Shunt-wound dynamo.

The field-magnets, of course, lose their strength when the current ceases to flow, but the cores usually contain enough residual magnetism to

cause the machine to develop sufficient current to "pick up" on the start.

580. Electric Motor with Bipolar Armature. The purpose of the electric motor is to transform electric energy into mechanical motion. The action of a simple series-wound motor is illustrated in Fig. 665, (1)-(5). The field-coil connections are shown only in diagram (1), with the pole-piece C a north and D a south pole.

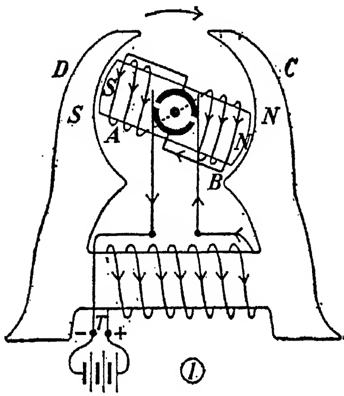


FIG. 665, (1)—Series-wound bipolar motor.

Electrical connections for leading the current in and out of the armature are made by brushes which make contact with semicircular commutator segments. These segments are joined to the ends of the coils on the armature pole-pieces. The direction of the current-flow in these coils for typical

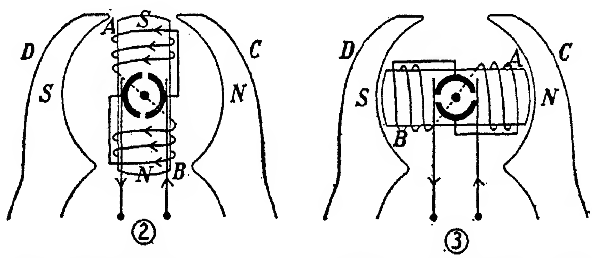


FIG. 665, (2) and (3).—Two typical positions of the armature in a bipolar motor.

positions of the armature is indicated in diagrams (1) to (5).

In position (1) the armature pole-pieces A and B are S and N, respectively and they are repelled by the adjacent field-poles D and C, producing a clock-wise rotation of the armature. In position (2) the couple producing rotation is a maximum. The magnitude of this couple then diminishes

until it becomes zero in position (3). The angular momentum of the armature is usually able to carry it past this position of zero couple and allow the commutator segments to interchange the brushes with which they make contact, as shown in diagram (4). In consequence of this change in the direction of the current in the armature coils their polarity is

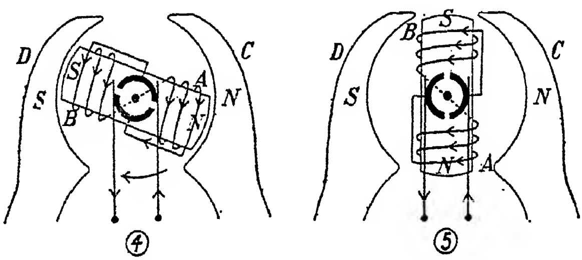


FIG. 665, (4) and (5).—Two succeeding positions of the armature.

reversed. The pole A is now an N-pole and B is a S-pole, and the forces of repulsion act to keep the armature rotating in a clock-wise direction. Position (5) is analogous to position (2) except that armature pole-pieces and commutator segments are interchanged.

If the battery connections, shown at T in Fig. 665 (1), are inter-changed, the polarity of both the armature and the field-magnets is reversed and the direction of rotation is unchanged. On account of this property motors of this type will operate on both alternating and direct currents. To avoid "eddy" currents in the iron cores of the armature and the field-magnets when alternating currents are used, the cores should be laminated, *i.e.* built up from thin iron plates separated by shellac or other thin insulator. Motors designed to operate on both alternating and direct currents are sometimes called "universal" motors.

EXERCISE AND QUESTIONS

Make a set of diagrams, and explain the action of the three-pole armature illustrated in Fig. 666. To simplify the diagram the brushes

are shown on the inside of the commutator instead of in their normal position on the outside.

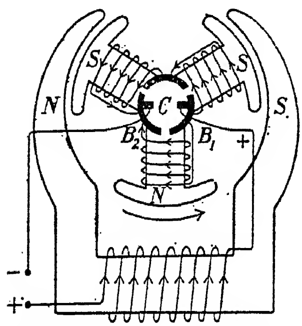


FIG. 666.—Motor with a three-pole armature.

What is the main advantage of this type of armature over the bipolar type?

How could the direction of rotation of the armature of the motor be reversed?

581. The Dynamo as a Motor.

As a general rule an electrical machine which serves as a dynamo can also be used as a motor. The motors described so far are similar in principle to the direct current dynamos illustrated in Figs. 660-664. The drum armature which is so often found in direct current dynamos (Figs. 654, 662) is also frequently used in direct current motors as it is more efficient than the pole-type of armature. For details regarding the winding in this type of motor the student should consult more advanced text-books on electricity.

If a source supplying alternating current is connected to an alternating dynamo it will run as a motor provided some means is employed to start it. This can be illustrated in the following way.

Experiment. Connect the terminals of a telephone magneto in series with a lamp resistance to the 25-cycle 110-volt mains, adjusting the automatic switch provided with this magneto so that it does not open the circuit when the magneto is started. Continue turning the crank faster until the rotor is brought up to operating speed and it will then run as a motor with a speed of 25 revolutions per second. This type of motor is called a synchronous motor. A simple type of synchronous motor is used in electric clocks.

Another more common type of alternating current motor is known as an induction motor. It is self-starting and is more convenient to use than the synchronous motor. The driving mechanism of the watt-hour meter (§ 611) is a simple form of induction motor. Further information on this subject cannot be given here.

582. Counter-Electromotive Force in the Motor.

As the armature of the motor is revolved it will, as in the dynamo, develop an E.M.F. opposite to that of the current causing the motion. The higher the speed of the armature, the greater is this counter-E.M.F. The shunt-wound electric motor is, therefore, self regulating for different loads. When the load is light, the speed becomes high and the increase

in the counter-E.M.F. reduces the amount of current passing through the armature coils; on the other hand, when the load is heavy the velocity is decreased and the counter-E.M.F. is lessened, allowing a greater current for increased work.

When the motor starts from rest there is, at the beginning, no counter-E.M.F., and the current must be admitted to the armature coils gradually through a rheostat (a set of resistance coils), to prevent the overheating of the wires and the burning of the insulation.

QUESTIONS AND PROBLEMS

1. Upon what is the potential difference between the brushes of a dynamo dependent?

2. Why is more power needed to drive a dynamo delivering 20 amperes current than when delivering 10 amperes?

3. How should a dynamo be wound to produce (1) currents of high E.M.F.; (2) a current for electroplating?

4. Why would an armature made of coils wound on a wooden core not be as effective as one with an iron core?

5. What would be the effect of moving the brushes of a dynamo backward and forward around the ring of commutator plates? Explain.

6. A direct-current motor is being used to drive a circular saw. An ammeter is in series with the motor. What changes will be noticed in the ammeter reading as the saw enters and leaves a piece of wood? Explain.

7. The motorman on a street-car moves his handle around slowly, admitting the current to the motors gradually. Why not move the handle completely around at once?

8. The swinging coil of a D'Arsonval galvanometer can be brought to rest quickly by short-circuiting the terminals. Explain.

CHAPTER LXXXI

TRANSFORMERS AND TELEPHONES

583. The Transformer. This is one of the most important applications of electromagnetic induction and we shall begin our study of it experimentally.

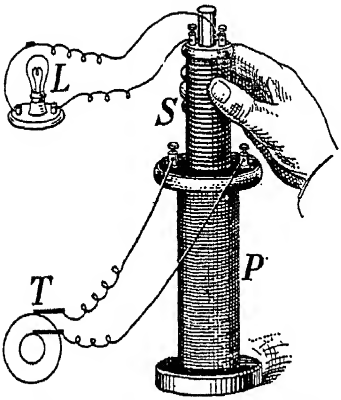


FIG. 667.—Experiment illustrating the transformer.

Experiment 1. Let us employ the two coils used in § 566. Attach the terminals of the coil P (Fig. 667), which has many turns of wire, to a magneto or other small A.C. dynamo T. Insert in the smaller coil S, which has only a few turns of coarser wire, a rod of iron or preferably a bundle of iron wires, and join the terminals of the coil to a small lamp L. On operating the dynamo the lamp lights up.

An alternating current in the coil P magnetizes the iron core in one direction and then rapidly magnetizes it in the opposite direction, and keeps up this action. This continual rapid reversing of the magnetic flux within and around the coil S induces in it an alternating E.M.F. The current in the coil depends not only on the E.M.F. but also on the resistance of the circuit of which it forms a part. With a suitable combination the lamp lights up.

This combination of coils, one acting on the other by electro-magnetic induction, illustrates the principle of the **transformer**, a device for changing an alternating current of one E.M.F. to an alternating current of another E.M.F. When the change is from low to high E.M.F., it is a **step-up** transformer; when from high to low, a **step-down** transformer. The coil P is called the **primary** coil, and the coil S the **secondary** coil.

Experiment 2. The transformer in Fig. 667 (which is a step-down) is inefficient in operation on account of the nature of the magnetic field

about a straight iron core. The form of core shown at T in Fig. 668 is much more efficient. It is a frame made up of stamped-out thin plates of soft-iron separated from each other by a coat of varnish.

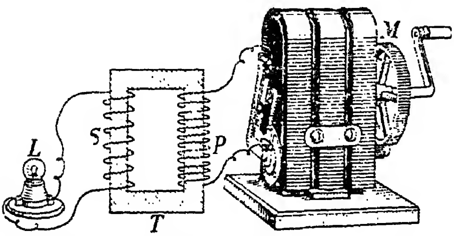


FIG. 668.—Small alternator and step-down transformer.

When a current is sent by the small A.C. dynamo M through the primary coil P it induces in the iron core within the coil magnetic lines of force which run through this core and finish their circuits by going completely round through the iron frame, thus passing through the core within the secondary coil S. When the current is reversed by the alternator the magnetic lines are reversed in both the coils P and S and thus an alternating E.M.F. is induced in S. In this case there are fewer turns in the secondary coil S and the voltage in it is lower than in the primary P. The coil S is joined to the small flash-light bulb L and when the dynamo is rotated the bulb lights up.

Experiment 3. If we join the alternator M to the coil which has the fewer turns, that coil becomes the primary P as in Fig. 669 and we get

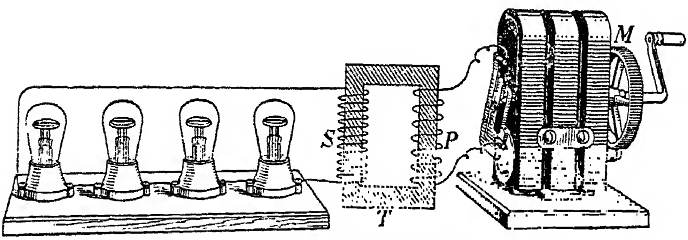
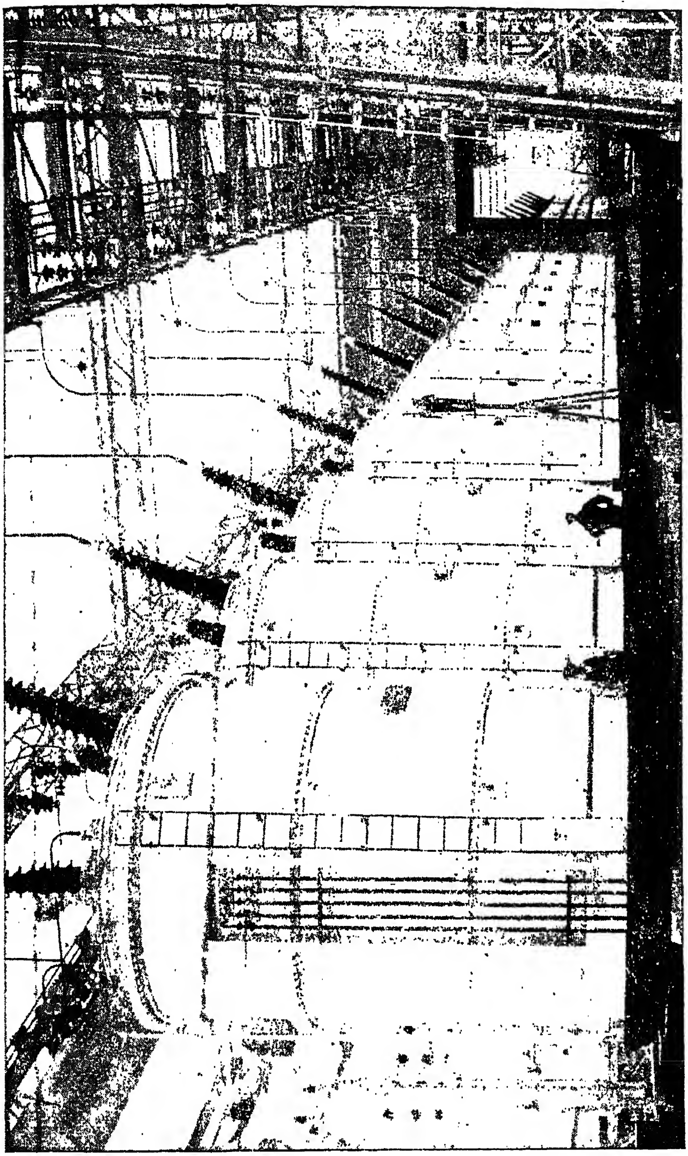


FIG. 669.—Small alternator and step-up transformer.

a step-up transformer, the voltage in S being higher than that in P. By speeding up the alternator we soon get a voltage high enough to light up the neon lamps in circuit with S. For this experiment a convenient transformer T is the power transformer of a B-battery eliminator in a radio receiving set.

584. Commercial Transformers. Transformers used for commercial purposes are of two general types: first, transformers of the core type in which the primary and secondary coils are wound about two parallel sides of a rectangular



TRANSFORMERS AT LEASIDE, NEAR TORONTO

Plate 33

The 220,000-volt current transmitted by the Ottawa-Toronto line is received by these transformers and stepped down to 13,200 voltage. The transformers are immersed in oil in the great tanks, and the capacity of each is 45,000 kilovolt-amperes.

(Photograph from the H.E.P.C. of Ontario)

core, as shown in Fig. 670; and second, of the shell type, in which the coils are wound about a core shaped in the form of ◫. The inner coils (Fig. 671) are the primary, and the

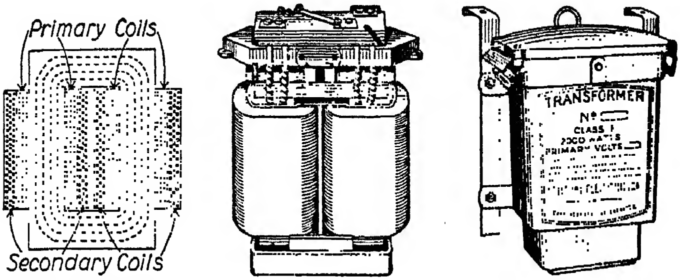


FIG. 670.—Core-type transformer, showing a vertical section, a general view and the transformer in its case on a pole.

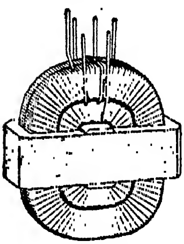


FIG. 671.—The shell-type transformer.

outer the secondary. In the first type the cores are within the coils, and in the second the core is built around the coils.

The electromotive force of the current generated in the secondary coil is to that of the primary current nearly in the ratio of the number of turns of wire in the secondary coil to the number in the primary.

For example, if the primary of a transformer has 200 turns and the secondary has 1000 turns, the voltage at the terminals of the secondary coil will be nearly 550 volts when an E.M.F. of 110 volts is applied to the primary. It must be noted, however, that if a current of 2 amperes is taken from the secondary, 10 amperes (at least) must flow in the primary. The power in watts furnished by the secondary, which is obtained by multiplying the current by the voltage (2 × 550) can never be greater than that being used in the primary (10 × 110). With the numbers given, the transformer would be 100% efficient. In actual practice the efficiency of the best transformers is about 97%.

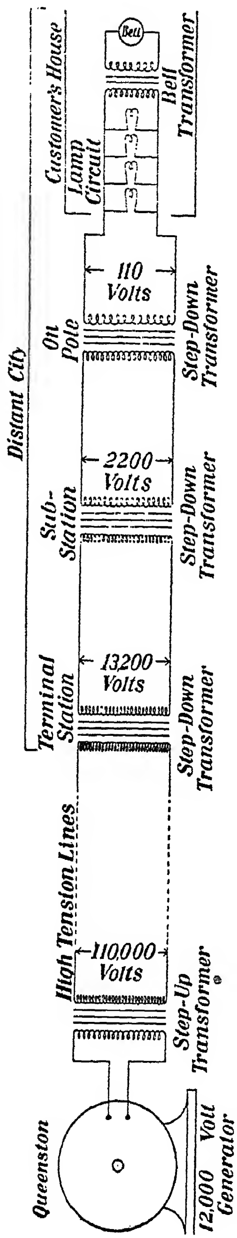


FIG. 672.—Diagram showing the different transformations which take place between Queenston and a house using Hydro-Electric Power.

585. Uses of the Alternating Current. On account of the facility with which the E.M.F. of an alternating current may be changed by a transformer, alternating currents are now usually employed whenever it is found necessary or convenient to change the tension of a current. The most common illustrations are to be found in the long distance transmission of electricity, where the currents generated by the dynamos are transformed into currents of very high E.M.F. for transmission, and again into currents of lower tension for use at the centres of distribution; and in the case of incandescent lighting, where it is advisable to have currents of fairly high tension in the street wires but, for the sake of safety and economy, currents of low E.M.F. in the lamps and house connections.

By stepping-up the voltage, the current-strength in the transmission wires is very much decreased (§ 584) and consequently the loss of energy through the development of heat in the conductor is lessened.* Also, because of the smaller current smaller conductors can be used and the cost of construction lowered. In the Hydro-Electric system which supplies many centres of Ontario

*The heating is proportional to the square of the current (§§ 588, 612).

with electric energy, the current when first generated at Niagara Falls is at a potential of 12,000 volts. It is then transformed to 110,000 volts and transmitted over well-insulated lines. On arriving at its destination it is transformed down again for use in lighting, power and heating.

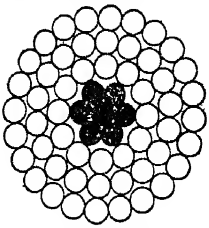


FIG. 673.—Section (actual size) of cable carrying 220,000-volt current. The 64 aluminium wires on the outside carry the current, while the 7 steel wires at the centre give strength to the cable.

In Fig. 672 is shown the different transformations which take place between Queenston and a house using Hydro-Electric power. In Fig. 673 is shown a section of one of the cables carrying the high-tension current from the Ottawa River to Leaside, near Toronto.

586. Telephone. The essential parts of a telephone set are a transmitter, a receiver, a signal system and sources of electric currents for the operation of the telephone circuits.

A diagram of a telephone receiver is given in Fig. 674. Electric currents of varying strength, flowing through the electromagnet coils *C*, *C*, cause variations in the force of attraction exerted by the horse-shoe magnet on the iron diaphragm *D*.

In Fig. 675 is shown a section of a modern transmitter. It is enclosed in a metal case of which *B* is the front and *C* the back. Into *B* the mouthpiece *A* is screwed. Behind this is the soft-iron diaphragm *E*, which is separated from *B* by the insulating washer *w*, *w*. The essential part of the transmitter is the carbon microphone. In a shallow round brass box granules of carbon *F*, in appearance resembling coal dust, are loosely packed. The front of the box is a thin disc of mica *m*, *m*, which carries a brass button *G*. In the front of this button is a non-conducting plug which rests against the centre of the diaphragm *E*. The brass box, or capsule, is fastened by a screw to a short brass rod *H*, and this is carried by a bent metal strip *D*.

The electric circuit is as follows. Let a current enter by a wire attached to L, which is insulated from D by mica washers o, r. It passes along the spring M to G, through the carbon granules to H, which is insulated from D by a mica washer n, n. Thence it leaves by a wire joined to J by the screw K. The two wires are led out through the hole N.

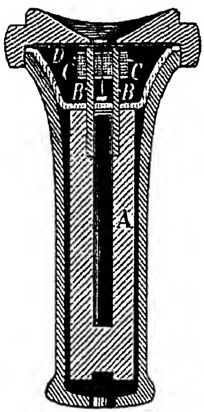


FIG. 674.—Telephone receiver.
A, permanent horse-shoe magnet; B, soft-iron pole-pieces; C, coils of fine wire D, iron diaphragm.

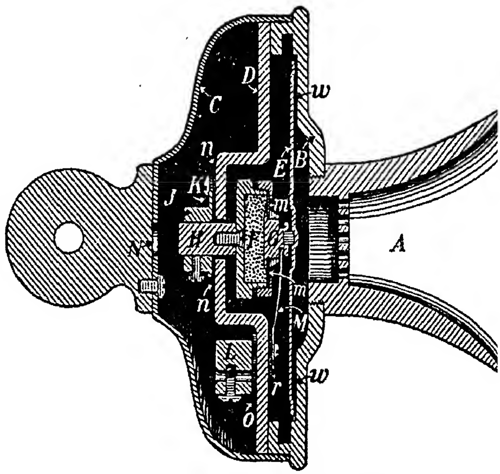


FIG. 675.—The microphone transmitter used in the Bell system, about half natural size. A, mouthpiece; E, iron diaphragm; F, carbon granules of the microphone· K and L, terminals to which wires are joined. They pass out through N.

The connections of the instruments in the complete circuit are shown in Fig. 676. The transmitter acts on the principle

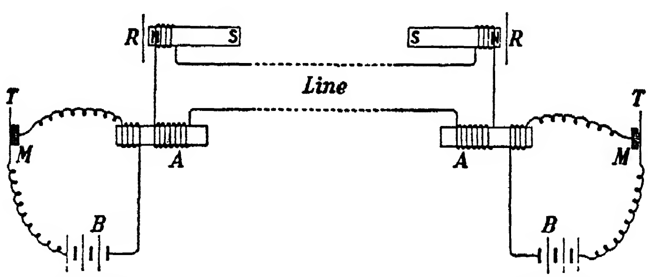


FIG. 676.—Diagram of telephone circuit. T, transmitter; M, carbon microphone; B, battery; A, step-up transformer; R, receiver.

that the conductivity of the granular carbon varies with the varying pressure exerted upon it as the diaphragm vibrates under the action of the sound waves. The current passing from the battery through the primary coil of a transformer *A* will, therefore, be fluctuating in character and will induce a current of varying strength and varying direction, but of higher electromotive force, in the secondary coil which is connected in the main line with the receiver. This current will cause corresponding variations in the magnetic state of the electromagnet of the receiver and thus set up vibrations in its diaphragm, which will reproduce the sound waves that caused the diaphragm of the transmitter to vibrate.

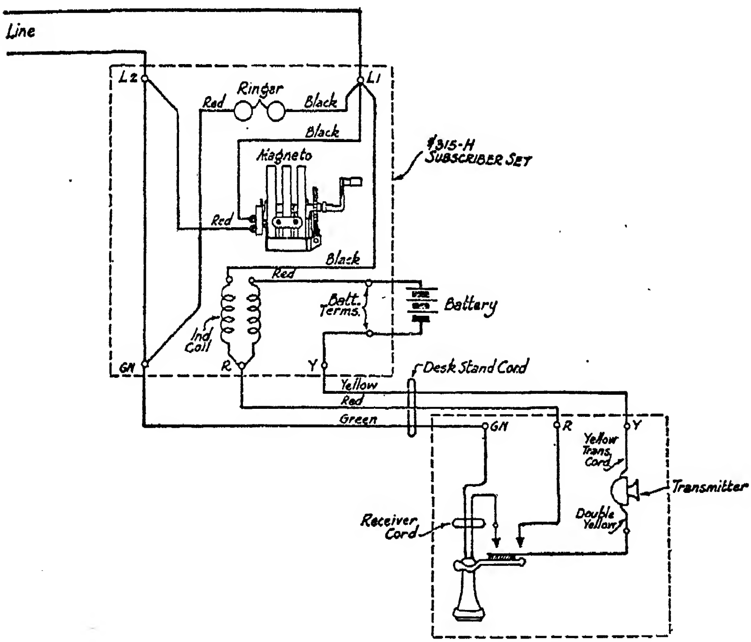


FIG. 677.—Diagram of connections of a rural telephone set.

587. Rural Telephone System. The connections for a complete unit of a rural telephone system are illustrated in Fig. 677. When the telephone is not in use the receiver is placed on a hook which disconnects

the battery from the circuit containing the transmitter. The ringer, however, remains connected across the line.

To put in a call, the telephone user turns the handle of the magneto. This automatically closes a switch at the end of the magneto and connects it to the line in parallel with the ringer. The alternating currents generated by the magneto give a signal in other telephone units connected in the party line and at the central station. If a person on another line is desired, Central signals the party asked for and makes the necessary connections by means of leads which terminate at the panel before which the operator sits. The windings in the ringer have a high resistance and as a consequence the current diverted by it from the line when the receiver is connected to carry on conversation is negligible. Simply removing the receiver connects in series the transmitter, the battery and the primary of the transformer, while at the same time the secondary coil of the transformer is linked in series with the receiver to the telephone line.

In a city system a central battery or dynamo is used in place of individual batteries. In addition to this, the removal of the receiver from its hook completes a circuit which lights a small lamp at Central without the use of a magneto.

In the modern automatic telephone systems the connections between the person calling and the party called are automatically made when the proper call letters and numbers have been dialled. When there are many subscribers the connections at the automatic exchange become very complicated.

REFERENCES FOR FURTHER INFORMATION

JACKSON and BLACK, *Elementary Electricity and Magnetism.*
BRAGG, *Blectricity*, Chapter III.

CHAPTER LXXXII

HEATING AND LIGHTING BY THE ELECTRIC CURRENT

588. Heat Developed by an Electric Current. In discussing the sources of heat (§ 178) we referred to the fact that, whenever an electric current meets with resistance in a conductor, heat results. Now, as no body is a perfect conductor of electricity, a certain amount of the energy of the electric current is always transformed into the energy of molecular motion. Joule, who investigated this subject, found, by comparing the results of numerous experiments, that in a given time **the number of heat units developed in a conductor varies as its resistance and as the square of the strength of the current.**

589. Practical Applications. Resistance wires heated by an electric current are used for various purposes, such as performing surgical operations, igniting explosives, cooking, heating, etc. In electric toasters and flat-irons the resistance wire is nichrome, an alloy of nickel and chromium. This can be kept at a red heat for weeks without injury, whereas an iron wire would soon deteriorate.

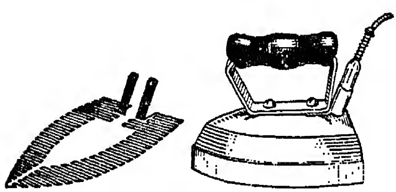


FIG. 678.—View of an electric iron and of its heating element.

Fig. 678. shows the arrangement of the resistance in an electric iron. A current of 5 to 6 amperes passes through the ordinary toaster or flat-iron used on a 110-volt circuit, which means that the power required to operate the appliance is 550 to 660 watts.

590. Safety Fuses. When too great a current passes through any electrical machine or appliance, excessive heat is developed and the machine may be ruined through the insulation being burned or the conductors being melted. To

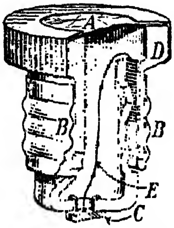


FIG. 679. — Ordinary screw plug fuse. *A*, mica; *B*, screw contact; *C*, tip contact; *D*, porcelain insulator; *E*, fuse wire.

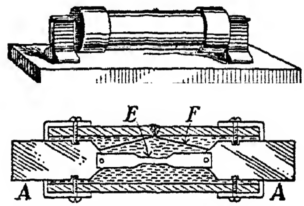


FIG. 680.—A cartridge fuse. The complete fuse inserted in the circuit is shown above, a longitudinal section below. *A*, *A*, contact strips of copper; *E*, fuse wire; *F*, a wire which chars the casing when the fuse melts.

prevent such injury, fuses, usually made from an alloy of lead which melts at a comparatively low temperature, are inserted in the circuit. If by accident too heavy a current is used, the fuse wire melts and opens the circuit. Two types of fuse in common use are shown in Figs. 679, 680.

591. Electric Furnace. In Fig. 681 is shown one kind of electric furnace. Carbon rods *C*, *C* pass through the asbestos walls of a chamber about 4 in. long, 2½ in. wide and 1½ in. high. Between them is a small crucible, and the space about is packed with granular carbon (arc lamp carbon rods broken into pieces about as large as coarse granulated sugar). The furnace is joined to an electric-lighting circuit through a rheostat. The resistance of the granulated carbon is considerable, and sufficient heat can be generated to melt pieces of copper in the crucible. This is a **resistance** furnace. Carborundum is produced from coke, sand, salt and sawdust in large furnaces of this type.

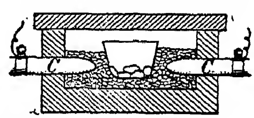


FIG. 681.—Electric resistance furnace.

In the arc furnace the heat is produced at a break in the circuit, as illustrated in the arc lamp (§ 595).

592. Electric Welding. Rods of metal are welded by pressing them together with sufficient force while a strong current of electricity is passed through them. Heat is developed at the point of junction, at which place the resistance is greatest, and the metals are softened and become welded together.

593. Incandescent Lamp. The construction of the incandescent lamp in common use is shown in Fig. 682. A slender tungsten filament is attached to leading-in wires and inclosed in a pear-shaped globe, from which the air is then exhausted. The leading-in wires are made from an alloy of copper, nickel and iron which has the same coefficient of expansion as lead glass and can be fused into it. When a sufficiently strong current is passed through the filament, it is heated to incandescence and yields a bright steady light.

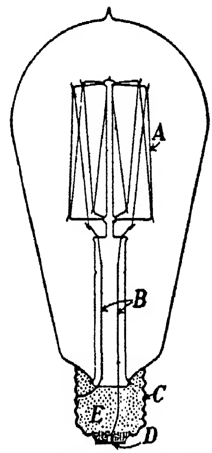


FIG. 682. — An incandescent lamp. *A*, tungsten filament; *B*, leading-in wires; *C*, screw base to which one wire is soldered the other being soldered to the tip *D*; *E*, cement.

The filament does not burn, for lack of oxygen to unite with it, but is very slowly vaporized when in use, depositing a dark metallic coating on the inner surface of the glass.

In another type of lamp the bulb is first exhausted of air and then filled with nitrogen. The presence of this gas retards vaporization and the tungsten filament may be kept at a higher temperature than in the vacuum lamp. The 'nitrogen' lamp gives for the same current a much higher candle-power than the ordinary tungsten lamp, because the increase in candle-power is proportionately greater than the increase in current necessary to produce the

extra heat in the filaments. To reduce the cooling effect of the gas, the filaments are coiled into spirals, allowing a long filament to be crowded into a small space. In addition, the convection currents set up in the gas by the heated filaments tend to deposit the metallic coating formed by vaporization at the top of the lamp and to leave the glass below undimmed.

Incandescent lamps are now usually rated in watts. For example, a 55-watt, 110-volt, lamp requires ½ ampere to light it properly.

The ordinary vacuum tungsten lamp requires about 1·25 watts per candle power while the gas-filled type operates on about 0·8 watt per candle power. The older type of carbon filament lamp required between 3 and 4 watts per candle power.

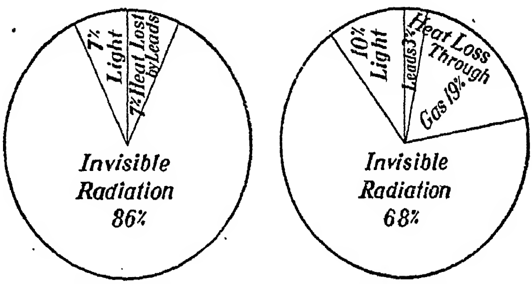


FIG. 683.—Distribution of energy in a tungsten filament lamp.

Despite the many improvements in electric lamps the energy corresponding to the visible light emitted is only a small part of the input of electrical energy. For the ordinary tungsten lamp the light emitted represents 7% of the input and for the gas-filled lamp the corresponding value is 10%. The remainder of the energy is given out as heat and invisible radiation. A diagram showing the transformations of energy in tungsten lamps is given in Fig. 683.

594. Heating Appliances. Electric stoves are now widely used. In the ordinary electric plate the coils are made of special heat-resisting wire and are wound in two sections. By means of the control switch these sections may be connected to the mains in three combinations: (*a*) with the sections in parallel, (*b*) with one section in the circuit and

(c) with the two in series, as illustrated in Fig. 684, a, b, c. These connections correspond to the 'High', 'Medium' and 'Low', respectively, of the stove dial.

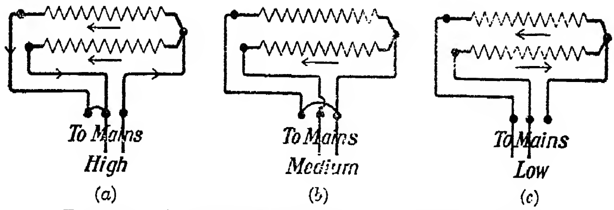


FIG. 684.—Arrangement of coils in an electric stove plate.

595. Arc Light. If two carbon rods, connected by conductors to the poles of a sufficiently powerful battery or dynamo, are touched together and then separated a short distance, the current continues to flow across the gap, developing intense heat and raising the terminals to incandescence, thus producing a powerful light, generally known as the **arc light.**

When the carbon points are separated by air only, the potential-difference between them when connected with the poles of an ordinary arc-light dynamo, is not sufficient to cause a spark to pass, even when they are quite close together; but if they are in contact and then separated while the current is passing through them, the "extra-current" spark produced on separation (§ 570) volatilizes a small quantity of the carbon between the points and a conducting medium, consisting of carbon vapour and heated air, is thus produced, through which the current continues to flow.

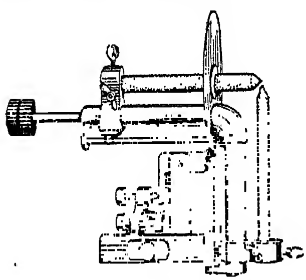


FIG. 685.—Hand-feed arc lamp.

Intense heat is developed and the carbon points become vividly incandescent and burn away slowly in the air. When a direct current is used, the point of the positive carbon

becomes hollowed out in the form of a crater, and the negative one becomes pointed, (Fig. 685). The greater part of the light is radiated from the carbon points, the positive one being the brighter.

Sodium Lamp. This lamp is designed for highway lighting. It consists of a glass tube about 12 inches long and 3 inches in diameter from which the air has been removed and some pure sodium introduced into it. Electrodes at the ends are joined to an A.C. circuit. On heating the lamp by suitable means some sodium is vaporized and electric discharges take place between the electrodes. A brilliant yellow light is emitted. The tube must be kept at about 480°F. and to conserve its heat it is enclosed in a double vacuum flask. It is more than twice as efficient as an incandescent lamp.

596. Hot-wire Ammeter. The extension which a wire experiences, when heated by a current passing through it, is utilized in the hot-wire ammeter (Fig. 686) to measure the strength of the current. The current to be measured enters by either of the binding-posts A, A, and traverses the rigid bar and the fine wire C, C before leaving by the other binding-post. To the wire C at the point a a wire D, D is attached and at the point b in this wire a thread E is attached. This thread passes around the drum e and the other end is fastened to the end of the spring F which keeps the thread and the two wires taut.

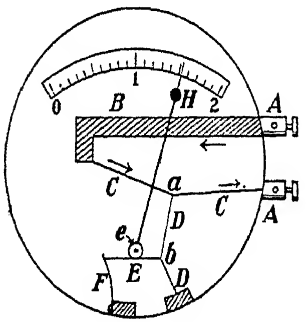


Fig. 686.—The principle of the hot-wire ammeter.

The current passing through C, C raises its temperature and causes it to lengthen. A small elongation of C, C causes a considerable movement of the end of the hand H which is attached to the drum.

The instrument can be calibrated by being placed in series with a voltameter or a standard ammeter. It has the disadvantage of requiring frequent adjustment, but on the other hand it can be used for measuring alternating as well as direct currents, while an ammeter of the type described in § 558 will not respond to an alternating current.

CHAPTER LXXXIII

ELECTRICAL MEASUREMENTS

597. Measurement of Resistance by Ammeter and Voltmeter. In setting up an electrical circuit it is very important to know the resistance of each part of it. This is particularly true in the transmission of electricity over long distances.

A practical method of determining the resistance of a conductor is to connect in series the conductor, an ammeter and a battery and also to join a voltmeter to the ends of the conductor, as in Figs. 587 and 610. If the reading of the ammeter is I amperes, of the voltmeter is V volts, then by Ohm's Law the resistance $R = V/I$ ohms.

598. Resistance Boxes. Several accurate methods of determining the resistance of a given conductor consist in

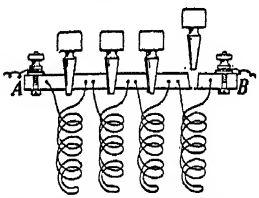


FIG. 687.— Connections in a resistance box.

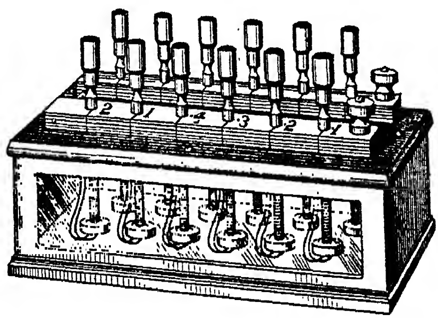


FIG. 688.—A resistance box with glass sides allowing the coils within to be seen.

comparing it, in suitable ways, with the resistance of certain accurately calibrated coils. Such coils are usually wound on bobbins and connected in sets in resistance boxes. Fig. 687 shows the common method of joining the coils. A current in passing from A to B meets with practically no resistance from the heavy metallic bar when all the plugs are inserted. To introduce a given resistance, the plug short-circuiting the proper coil is

removed and the current is made to traverse the resistance wire. For convenience in calculation the coils are usually grouped very much as weights are arranged in boxes. For example, a set of coils of 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500 ohms may be combined to give any resistance from 1 to 1000 ohms. Fig. 688 shows an ordinary form of resistance box.

599. Method of Substitution. To determine resistance by this method the conductor is placed in a circuit with a cell of constant E.M.F. and a sensitive galvanometer. The deflection of the needle of the galvanometer is noted, and the unknown resistance is then replaced by a resistance box. The coils are adjusted so as to bring the needle to its former position. The resistance thus placed in the circuit is evidently equal to the resistance of the conductor.

This method of substitution, was employed by Ohm in his first experiments. Obviously, variations in the E.M.F. of the cell used will introduce errors in the determination.

600. Wheatstone Bridge. Wheatstone, who was an English contemporary of Ohm and had followed his experiments, invented what is known as the Wheatstone Bridge, an arrangement of coils which makes the determination independent of changes in the E.M.F. of the cell. The coils are arranged in three sets A, B, and C, with connections for a battery, a galvanometer and the resistance to be measured, as shown in Fig. 689.

They are mounted in a box and the changes in the resistance are made in the usual way, by inserting or withdrawing conducting plugs, as shown in Fig. 687.

The branches B and C usually have three coils each, the resistances of which are respectively 10, 100 and 1000 ohms, and the branch A has a combination of coils, which will give any number of units of resistance from, say, 1 to 11,110 ohms. The conductor, whose resistance X is to be measured is

inserted in the fourth branch of the bridge (Fig. 689), and the resistances A, B and C adjusted until the galvanometer connecting M and N stands at zero when the keys are closed.

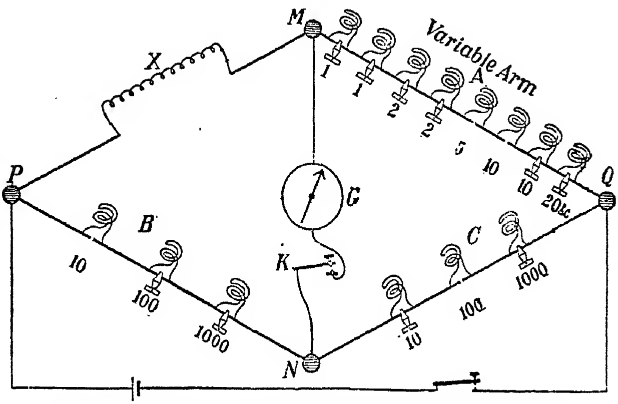


FIG. 689.—Diagram of connections in the Wheatstone Bridge.

Then the current from the battery is flowing from P to Q, partly through X and A, and partly through B and C, and since no current flows from M to N, the potential of M must be the same as that of N; therefore the fall in potential from P to M in the circuit PMQ is the same as the fall from P to N in the circuit PNQ; but the fall in potential in a part of a circuit is proportional to the resistance of that portion of the circuit.

$$\text{Hence, } \frac{X}{A} = \frac{B}{C} \text{ or } X = \frac{B}{C} \times A.$$

The resistances A, B and C are read from the instrument, and the value of X is calculated from the formula.

Example. In an experiment B was 10, C 1000 and A 3378 ohms. Then $X = 33.78$ ohms.

601. Slide-wire Bridge. A simple form of bridge is shown in Fig. 690. Here a piece of German silver wire a metre long and about 0·5 mm. in diameter is made to serve the purpose of both the resistances B and C of Fig. 689. The unknown resistance X, the variable resistance box A, the galvanometer G, key K, and battery are connected as before.

One terminal of the galvanometer is joined to M, a binding-post on a metal bar to which X and A are both joined, and the other to a sliding contact N, by moving which the ratio B/C can be varied at will.

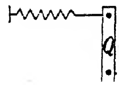


FIG. 690.—The slide-wire bridge.

The slide-wire contact is first placed at the centre of the wire and an approximate balance is secured by altering A. The contact is then moved until a perfect balance is obtained.

602. Laws of Resistance. The resistances of conductors under varying conditions have been determined by various investigators with great care. The general results are given in the following laws:

1. The resistance of a conductor varies directly as its length.

2. The resistance of a conductor varies inversely as the area of its cross-section.

3. The resistance of a conductor of given length and cross-section depends upon the material of which it is made.

Hence, if l denotes the length of a conductor, A the area of its cross-section and R its resistance,

$$R = k\frac{l}{A},$$

where k is a constant depending on the material of the conductor and the units of measurement used. The constant k is known as the **Specific Resistance** of the material. For scientific purposes the specific resistance is usually expressed as the resistance in microhms, or millionths of an ohm, of a cube of this material, whose edge is one centimetre in length, when a current is made to flow parallel to one of its edges.

In engineering practice resistance is usually calculated in another way. Designating $\frac{1}{1000}$ inch as 1 mil, the standard of resistance is the resistance of a wire 1 mil in diameter and 1 foot in length. This is named

a-mil-foot. The resistance per mil-ft. of copper is 10·4, of aluminium 17·0 ohms, etc.

The accompanying table gives the specific resistances in microhms and the resistance per mil-foot in ohms of some well-known substances, at 20° C. unless otherwise stated.

SPECIFIC RESISTANCE AND RESISTANCE PER MIL-FOOT*

Substance	Sp.R.	M.-ft.	Substance	Sp.R.	M.-ft.
Aluminium wire.....	2·83	17·0	Chromium......	2.6	15.6
Carbon (filam't) 0° C.	3500	21,070	Nickel..........	7.8	46.9
" " 1500° C.	1500	9,030	Nichrome wire...	100	602
Copper wire.........	1.72	10.4	Platinum wire...	10	60.2
German silver 18% Ni.	33	198·7	Silver wire......	1·63	9·8
Iron wire (pure).....	10	60·2	Tungsten, 20° C.	5·5	33·1
Steel rails...........	11·9	71·6	" 1727° C.	59	355·2
Mercury............	95·8	576·7	" 3227° C.	118	710·4

Observe that the specific resistance of chromium is 2·6 and that of nickel is 7·8, while nichrome, an alloy of these two substances, has a specific resistance of 100.

603. Resistance and Temperature. If we connect a piece of fine iron or platinum wire in a circuit with a voltaic cell and a galvanometer and note the deflection of the needle, we shall find on heating the wire with a lamp that the galvanometer indicates a weakening of the current. The rise in the temperature of this wire must, therefore, have been accompanied by an increase in its resistance. This action is typical of metals in general.

The resistance of nearly all pure metals increases about 0·4 per cent. for each rise in temperature of 1 centigrade degree. The resistance of carbon, on the other hand, diminishes when heated. The filament of an old style incandescent carbon lamp, for instance, has when hot only about one-half the resistance which it has when cold. The resistance of an electrolyte also decreases with a rise in temperature.

It is often necessary to know the strength of current which can be carried safely by wires of different diameters. In the following table is given the carrying capacity of insulated copper wires of the ordinary sizes.

*The number in the third column is 6.02 times that in the second. This can be deduced from the laws of resistance and the ratio of an inch to a centimetre.

CARRYING CAPACITY OF COVERED COPPER WIRES

Size of Wires			Insulation	
B. & S. Gauge	Diam. in Mils	Diam. in mm.	Rubber	Weather-proof
18	40·3	1·02	3 amp.	5 amp.
16	50·8	1·29	6 "	8 "
14	64·1	1·63	12 "	16 "
12	80·8	2·05	17 "	23 "
10	101·9	2·59	24 "	32 "
8	129·5	3·26	33 "	46 "

QUESTIONS AND PROBLEMS

1. What length of wire would be required for a 100-ohm resistance coil if a sample 1 ft. long has a resistance of 0·4 ohm?

2. Copper wire $\frac{1}{12}$ inch in diameter has a resistance of 8 ohms per mile. What is the resistance of a mile of copper wire the diameter of which is $\frac{1}{36}$ inch?

3. A mile of telegraph wire 2 mm. in diameter offers a resistance of 13 ohms. What is the resistance of 440 yards of wire 0·8 mm. in diameter made of the same material?

4. What length of copper wire, having a diameter of 3 mm., has the same resistance as 10 metres of copper wire having a diameter of 2 mm.?

5. On measuring the resistance of a piece of No. 30 B.W.G. (covered) copper wire 18·12 yards long I found it to have a resistance of 3.02 ohms. Another coil of the same wire had a resistance of 22·65 ohms. What length of wire was there in the coil?

6. Two wires of the same length and material are found to have resistances of 4 and 9 ohms, respectively. If the diameter of the first is 1 mm., what is the diameter of the second?

7. What must be the thickness of copper wire, which, taking equal lengths, gives the same resistance as iron wire 6·5 mm. in diameter, the specific resistance of iron being six times that of copper?

8. Find the length of an iron wire $\frac{1}{20}$ inch in diameter which will have the same resistance as a copper wire $\frac{1}{60}$ inch in diameter and 720 long, the conductivity of copper being six times that of iron.

9. A wire made of platinoid is found to have a resistance of 0·203 ohm per metre. The cross-section of the wire is 0·016 sq. cm. Express the specific resistance of platinoid in microhms.

10. Taking the specific resistance of copper as 1.58, calculate (1) the resistance of a kilometre of copper wire whose diameter is 1 mm., (2) the resistance of a copper conductor 1 sq. cm. in area of cross-section, and long enough to reach from Niagara to New York, reckoning this distance as 480 kilometres.

604. Resistance in a Divided Circuit; Shunts. When a current is divided and made to flow from a conductor A to another B through two parallel circuits (Fig. 691), it is often necessary to determine the resistance of a single wire, which will be equivalent to the two in parallel, and to find the fraction of the total current which flows through each wire.

FIG. 691.—Divided circuit.

Let V denote the difference in potential between A and B and R_1 and R_2 the resistances of the wires.

Then the current through the first wire $= V/R_1$ (Ohm's Law), and the current through the second wire $= V/R_2$.

Total current through the two wires $= V/R_1 + V/R_2$.

But the total current $= V/R$, where R is the resistance of a single wire equivalent to the two.

Therefore $\dfrac{V}{R} = \dfrac{V}{R_1} + \dfrac{V}{R_2}$, that is, $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$.

Again, the fraction of the total current in the first wire

$$V/R_1 + V/R_2 \qquad R_1 + R_2$$

Similarly, the fraction of the total current in the second wire

$$= \frac{R_1}{R_1 + R_2}.$$

When it is undesirable to send the whole current to be measured through a galvanometer or other current-measuring instrument, a

definite fractional part of the current is diverted by making the instrument one of two parallel conductors in the circuit, as shown in Fig. 692. The conductor R in parallel with the galvanometer G is called a shunt.

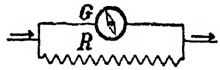


FIG. 692. — Galvanometer and shunt.

If G is the resistance of the galvanometer, R the resistance of the shunt, and I the total current, the amount of current through the galvanometer

$$- \frac{\quad}{G + R} \times I.$$

For the sake of facility in calculation, it is usual to make R $\frac{1}{9}$, $\frac{1}{99}$ or $\frac{1}{999}$ of G, when, by the above formula, the current through the galvanometer will be $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$, respectively, of the total current to be measured.

PROBLEMS

1. The poles of a voltaic battery are connected by two wires in parallel. If the resistance of one is 10 ohms and that of the other 20 ohms, find (1) the resistance of a single wire equivalent to the two in parallel; (2) the proportion of the total current passing through each wire.

2. Find the total resistance when the following resistances are joined in series:—$3\frac{1}{2}$ ohms, $2\frac{1}{3}$ ohms, $2\frac{1}{4}$ ohms. What would be the joint resistance if the resistances were joined in parallel?

3. What must be the resistance of a wire joined in parallel with a wire whose resistance is 12 ohms, if their joint resistance is 3 ohms?

4. The joint resistance of ten similar incandescent lamps connected in multiple is 10 ohms. What is the resistance of a single lamp?

5. Four incandescent lamps are joined in parallel on a 100-volt circuit. If the resistances of the lamps are respectively 100 ohms, 200 ohms, 300 ohms and 400 ohms, find (1) the total current passing through the group of lamps; (2) the proportion of the total current passing through the first lamp; (3) the resistance of a single lamp which would take the same current as the group.

6. A galvanometer whose resistance is 1000 ohms is used with a shunt. If $\frac{1}{11}$ of the total current passes through the galvanometer, what is the resistance of the shunt?

7. If the shunt of a galvanometer has a resistance of $1/n$ of the galvanometer, what fraction of the total current passes through the galvanometer?

8. The internal resistance of a Daniell cell is 1 ohm; its terminals are connected (a) by a wire whose resistance is 4 ohms, (b) by two wires in parallel one of the wires having a resistance of 4 ohms, the resistance of

the other wire being 1 ohm. Compare the currents through the cell in the two cases.

605. Grouping of Cells or Dynamos. Electrical generators may be connected in various ways to give a current in the same circuit.

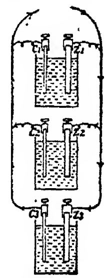


Fig. 694.—Cells connected in multiple.

They are connected *in series* or *tandem* when the negative terminal of one is connected with the positive terminal of the next (Fig. 693), and *in multiple*, or *parallel*, when all the positive terminals are connected to one conductor and all the negatives to another (Fig. 694).

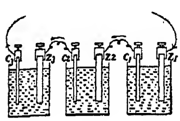


Fig. 693.—Cells connected in series.

606. Current Given by Series Arrangement. If n cells are arranged in series, and r is the internal resistance of each cell, it is evident that the resistance of the group $= nr$, because the current has to pass through a liquid conductor n times as long as that between the plates of a single cell.

If the potential-difference between the plates of a single cell (Fig. 693) is e, the potential-difference between Z_1 and C_1 is e; but when C_1 and Z_2 are connected by a short thick conductor there is practically no fall in potential between them, therefore the potential-difference between Z_1 and Z_2 is e. Again, the potential-difference between Z_2 and C_2 is e and therefore the potential difference between Z_1 and C_2 is $2e$. Similarly, for 3, 4, etc., cells the potential-differences are respectively $3e$, $4e$, etc. Hence, the E.M.F. of n cells in series is ne.

Suppose now that the group of cells is in circuit with an external resistance R_1.

By Ohm's law, $I = E/R$, where E is the E.M.F. of the group and R the total resistance of the circuit; but $E = ne$, and $R = nr + R_1$;

$$\text{Hence } I = \frac{ne}{+R}.$$

607. Current Given by Multiple Arrangement. If n cells are arranged in multiple, and r is the internal resistance of a single cell, the internal resistance of the group $= r/n$, because the current in passing through the liquid from one set of plates to the other has n paths open to it, and therefore the sectional area of the column of liquid traversed is n times that of one cell, hence the resistance is only $1/n$ of that of one cell (§ 602). When all the positive plates are connected they are at the same potential; for a similar reason all the negative plates are at the same

potential, hence the E.M.F. of n cells in multiple is the same as that of one cell.

This method of grouping is equivalent to transforming a number of single cells into one large cell, the Z plates being united to form one large Z plate, and the C plates to form one large C plate. It must be remembered that the potential-difference between the plates of a cell is independent of the size of the plates. (§ 521.)

If E is the E.M.F., R the total resistance of the circuit, and R_1 the external resistance,

$$I = \frac{E}{R} \qquad r/n +$$

PROBLEMS

1. If the E.M.F. of a Grove cell is 1·8 volts and its internal resistance is 0·3 ohm, calculate the strength of current when 50 Grove cells in series are connected to a wire whose resistance is 15 ohms.

2. If 6 cells, each with $\frac{1}{2}$ ohm internal resistance, and 1.1 volts E.M.F., are connected in series, calculate the current sent through a wire of resistance 0·8 ohm.

3. Calculate the number of cells in series required to produce a current of 50 milliamperes (1 milliampere = $\frac{1}{1000}$ ampere), through a line 114 miles long, whose resistance is $12\frac{1}{4}$ ohms per mile, the cells of the battery having each an internal resistance of 1·5 ohms, and an E.M.F. of 1·5 volts.

4. A circuit is formed of 6 similar cells in series and a wire of 10 ohms resistance. The E.M.F. of each cell is 1 volt and its resistance 5 ohms. Find the strength of the current.

608. Quantity of Electricity. Let us consider the flow of water through a pipe. The current strength is the rate of flow. It depends upon the difference of pressure at the ends of the pipe, and the resistance of the pipe. But we often wish to know the **quantity** of water passing in a given time. Obviously we have the relation,

$$\text{Quantity} = \text{rate of flow} \times \text{time of flow}.$$

We might measure rate of flow in gallons-per-second, and quantity in gallons.

In electrical measurements there is something similar. We may think of the quantity of electricity passing a cross-section of a circuit in a given time, and as before we have the relation,

Quantity of electricity = current strength × the time.

If we measure current strength in amperes, and time in seconds, the quantity will be given in **coulombs**; and we have the definition: **A coulomb is the amount of electricity which passes a point in a circuit in one second when the strength of the current is one ampere.**

The ampere corresponds to gallons-per-second, the coulomb to gallons.

If the strength of a current is I amperes and the quantity flowing past a point in the circuit in t seconds is Q coulombs, then $Q = It$.

As already stated in § 527, practical electricians frequently employ the **ampere-hour** as the unit quantity, as, for example, in estimating the capacity of a storage cell. A battery has a capacity of 100 ampere-hours, when it will furnish a current of one ampere for 100 hours, or 2 amperes for 50 hours, etc.

We may define here the capacity of a condenser. **A condenser has unit capacity when a charge of one coulomb raises its potential one volt.** This unit is the **farad** and as it is large the capacity of a condenser is usually expressed in **microfarads** (millionths of a farad).

Question.—What is the capacity in coulombs of a 100 ampere-hour storage battery?

609. Rate at Which Work is Done in an Electric Circuit. The power, or rate at which work is done in an electric circuit, is estimated in **joules per sec.**, that is, in **watts** (§ 534).

Thus if a current of I amperes flows through a circuit in which there is a drop of potential of V volts, energy is being delivered at the rate of VI watts.

Power (watts) = P.D. (volts) × Current (amperes).

Since one horse-power = 746 watts (§ 128)

$$\text{Power (in h.p.)} = \frac{\text{Pot. diff. (in volts)} \times \text{current (in amperes)}}{746}$$

610. Work Done in an Electric Lamp. For commercial purposes, the energy consumed by a lamp in a given time is usually measured in **watt-hours** or **kilowatt-hours** (1 k.w. = 1000 watts). For example, if a customer has a lamp requiring ½ ampere in a 110-volt circuit it uses 55 watts of power, and if it burns 100 hours per month he pays monthly for 55×100, or 5500, watt-hours, which is $5 \cdot 5$ k.w.h. of energy.

611. The Watt-hour Meter. The object of the watt-hour meter is to show the amount of electrical energy used each month by the customer of an electric power company. In Figs. 695, 696 is shown the outside appearance of an alternating-current watt-hour meter, and in Fig. 697 is a diagram illustrating its operation. In this instrument the essential working parts comprise an induction motor, control magnets and recording apparatus.

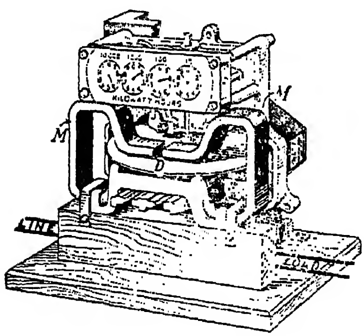


Fig. 695.—A watt-hour meter (front view).

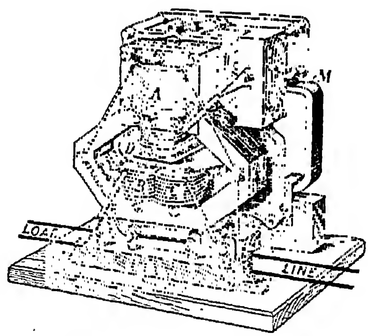


Fig. 696.—A watt-hour meter (rear view).

The induction motor in the meter consists of a pivoted disc D (Fig. 696) which is set in rotation by the action of the varying magnetic fields set up in the electromagnets A, B, and C. (See also Fig. 697). The coils in the magnets B and C consist of a few turns of coarse wire and they are connected in series with the wires carrying the currents in the circuits which are designated as 'Load', and consist of the lamps, motors, and other appliances used by the customer. The magnetic fields produced by these coils are proportional to the current flowing in the Load circuit.

The coil of the electromagnet A has a large number of turns of fine wire and is connected directly across the mains. Consequently the magnetic field produced in A is proportional to the potential difference

between the mains. With its coils connected to an alternating current circuit, the self-inductance in the coil A retards the growth and decay of the current therein as compared to the change in the coils B and C. The currents in the latter reach a maximum and commence to decline before the current in the coil A reaches a maximum. The changes in A are thus out of step with the changes in B and C. The magnetic poles formed adjacent to the disc for typical positions in one cycle, starting with the current a maximum value in the Load circuit, are shown in Fig. 697. The action on the disc is the same as if it were in the field of a rotating magnet as illustrated in § 564. Induced currents are set up in the disc which react with the moving magnetic field to produce a torque tending to rotate the disc. The magnets and disc are adjusted so that the driving torque is proportional to the input of watts into the Load circuit.

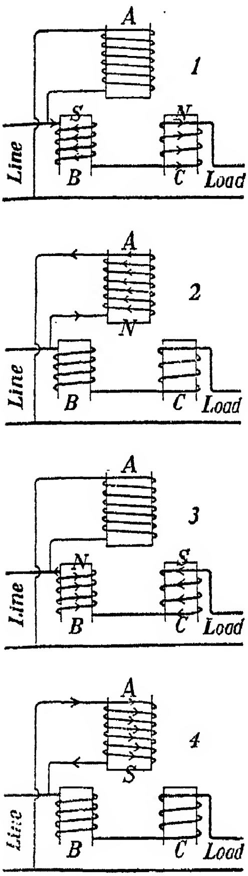


Fig. 697. — Typical magnetic cycle for A.C. watt hour meter electromagnets.

A retarding torque is provided by allowing the disc to rotate between the poles of a pair of horseshoe magnets M. The retarding torque set up by this method is proportional to the speed of rotation. Consequently, if electrical energy is being used in the Load circuit the disc in the meter rotates with a speed proportional to the power in the circuit.

The shaft attached to the disc operates a train of gears arranged so that the speed of each gear decreases by a factor of ten. The dials attached to the gears give a reading in kilowatt-hours of the energy used in the Load circuit.

612. Relation Between Heat Energy and the Energy of the Electric Current. The mechanical equivalent of heat is 4·2 joules per calorie, that is one joule = 0·24 calorie. Hence if an electric current of I amperes is flowing in a circuit in which there is a fall in potential of V volts, and all the energy of the current is transformed into heat, $V \times I \times 0{\cdot}24$ calories will be developed every second.

More frequently, however, the quantity of heat produced by a current is expressed in terms of the current and the resistance. By Ohm's law, $V = RI$; therefore the heat developed in a circuit, whose resistance is R ohms by a current of I amperes is $RI^2 \times 0{\cdot}24$ calories per second, or in t seconds the heat produced $= RI^2t \times 0.24$ calories. This accords with results determined experimentally by Joule (§ 588).

PROBLEMS

1. A current of 10 amperes flows through an arc light circuit. What quantity of electricity will pass across the arc of one of the lamps in a night of 10 hours?

2. The difference in potential between a trolley wire and the rail which carries the return circuit is 500 volts, and the motor of a car takes an average current of 25 amperes. Find the average power of the motor in

12.5 kw.

3. Find the power necessary to run an electric light installation taking 125 amperes at 110 volts (*a*) in k.w., (*b*) in h.p. 13¾ kw.

4. The potential difference between the wires entering a house is 104 volts, and an average current of 8 amperes flows through them for 4 hours per day. How many watt-hours of energy must the householder pay for in a month of 30 days? Find the cost at 8 cents per kilowatt-hour. $7

5. Find the cost per hour of operating an electric toaster which takes 6 amperes current at 110 volts pressure, if the rate is 5 cents per k.w.h.

6. How many 40-watt tungsten lamps can be lighted by the power used in operating an electric motor which uses 2 amperes current at 220 volts?

7. Find the smallest h.p. which a gas-engine can have which is used to drive a dynamo supplying current for twenty-five 60-watt 110-volt lamps in a farm lighting system. Would it make any difference if the lamps required 55 volts pressure?

8. In a motor-generator set the motor takes 6 amperes at 550 volts when the generator is supplying 27 amperes at 110 volts. Find the efficiency of the set.

9. The resistance of the filament of an incandescent lamp is 20 ohms and it carries a current of 6 amperes. Find the amount of heat (in calories) developed in this filament per minute.

REFERENCES FOR FURTHER INFORMATION

Jackson and Black, *Elementary Electricity and Magnetism.*
Weston Electrical Instrument Co., *Monographs.*

PART IX— OTHER FORMS OF RADIANT ENERGY

CHAPTER LXXXIV

ULTRA-VIOLET, INFRA-RED, ELECTRIC WAVES

613. Beyond the Visible Spectrum. We have seen that when white light is passed through a prism it is separated into its different components, and on a screen placed in its path (Fig. 478) we observe a spectrum, with its colours ranging from violet at one end to red at the other. The wavelength of the extreme red is 0·000,8 mm. or about $\frac{1}{30000}$ inch; that of the extreme violet is 0·000,4 mm. or about $\frac{1}{60000}$ inch. If we considered these waves as we do sound waves we would say that the visible radiation corresponds to one octave.

The question arises, are there radiations beyond those which give rise to the red and the violet sensations?

614. Waves beyond the Violet. In order to investigate this question let us receive the spectrum upon an ordinary photographic plate. Upon developing it, we find that while it has been scarcely affected by the red and the yellow light, the blue and the violet have produced strong action, and further, that decided action has been produced **beyond the violet.** By suitable means photographic action has been traced to wave-lengths of 0·000,02 mm., that is, to more than three 'octaves' above the violet.

Quite recently it has been shown that the X-rays (see § 635) are of the same nature but their wave-lengths are much shorter. The Gamma rays (§ 641) and also the Cosmic rays (§ 637) are similar in nature but with wave-lengths shorter still.

615. Beyond the Red. If we wish to explore beyond the red, we must use a sensitive detector of heat. Let us obtain

the spectrum of the sun, and then through it, going from blue to red, pass an air thermoscope (Fig. 284), the bulb of which has been coated with lamp-black. The thermoscope will show a heating effect which increases as we go towards the red, but the heating does not cease there. Beyond the red the effect is still pronounced. By means of special instruments, heat waves 0·3 mm. long have been detected and measured. Such waves are about ten 'octaves' below the longest red waves.

Bodies at ordinary temperatures emit heat waves, and as the temperature is raised they give out, in addition, those waves which affect the eye.

Still other waves are produced by electrical means and are utilized in radio telegraphy and telephony, which are briefly discussed in the next chapter.

TABLE OF WAVE-LENGTHS

Kind of Radiation	Wave-length Limits (approx.)	How Detected or Utilized
Hertzian waves......	2000 km. to 10 m..	Wireless or radio
Short electric waves..	10 m. to 0·03 cm..	Refraction or interference
Infra-red radiation...	0·03 cm. to 8000 A.	Heating; special photographic plates
Visible light.........	8000 A. to 4000 A..	The eye; photography
Ultra-violet radiation	4000 A. to 140 A...	Photographic plate
Soft X-rays.........	140 A. to 22 A.....	Photoelectric effect; ionization
X-rays......	22 A. to 0·1 A.....	Photographic plate; ionization; used in surgery
Gamma rays.	4·0 A. to 0·05 A....	Ionization of gas; treatment in medicine
Cosmic rays..	Perhaps 0·004 A...	Ionization of a gas

The unit abbreviated as A. is the angstrom, named after Angström, a Swedish physicist.

1 A. = 1 angstrom = 1 ten-millionth of a millimetre $= 1 \times 10^{-8}$ cm.

616. Radiant Energy. These waves of various lengths are all forms of radiant energy. While passing from one place to another they travel with the speed of light, and it is only when they fall upon some form of matter that their energy is transformed into those physical effects which we recognize as heat, light, and in other ways. The wave-lengths given in the nearby table are somewhat arbitrary, and may be exceeded in further experimenting.

617. Effects of Radiation on Plant Life. Plants in general use the energy of sunlight together with the carbon dioxide in the atmosphere and the water and mineral salts which constitute the sap to produce, by a process called **photosynthesis**, the food necessary for the growth and development of their cells. Not all the details of this process are known, but it takes place only when the green colouring matter chlorophyll is present. Many kinds of plants can be grown in total darkness. MacDougall* grew 97 different species. The growth, however, was not normal, for little or no chlorophyll was formed and the stems were tall and weak with thin partially-developed leaves.

Some plants show an increased rate of growth when the day in effect is lengthened by artificial light up to 24 hours, but the growth of many others seems hindered by such treatment, perhaps because they have had no opportunity, through many generations, to become adapted to it. We must remember also that no source of radiation gives light comparable in intensity and quality to midday sunlight in summer.

There are two points in the spectrum where the effect of illumination is greatest. One is near 6550 A. (deep red), the other near 4400 A. (blue). Light of these wave-lengths seems to be fundamental in the phenomena of life.

From experiment it appears that certain wave-lengths of light favour the germination of seed and that some prevent it. At the Smithsonian Institution† in 1935 it was found that while the yellow, orange and shorter red waves effectively promoted the germination of lettuce seed, a section of the spectrum just on the edge of the visible red, about 7600 A., had a marked restraining influence.

The X-rays and the rays from radium seem in general to be detrimental to the growth of green plants. Their action on seeds is peculiar, for

*New York Botanical Gardens. †Washington, D.C.

sometimes the new plant will differ from its parents in a decided way. We say that the rays have caused mutation.

618. Effects of Radiation on Animal Life. Sunlight is beneficial to most forms of animal life although some simple forms are destroyed by it. We do not receive the complete radiation sent out by the sun since the atmosphere prevents those ultra-violet waves, shorter than about 2900 A., from reaching the earth. This limit varies, however, with the height above sea-level and with the state of the atmosphere with respect to dust and clouds. Artificial sources have been devised to give the shorter ultra-violet radiation with considerable intensity. The chief source is the mercury arc produced in a quartz tube, but a carbon arc or an arc between iron or other metallic electrodes is also employed.

These short wave-lengths are very destructive to animal cells, which are always protected by the atmosphere. An exposure of a minute or two to a strong mercury arc will kill almost any sort of bacteria. Practical application of this fact is made in the sterilization of drinking water and in the purification of water for a swimming pool.

Animals and birds are usually protected by hair or feathers, but the human skin is affected even by strong sunlight and much more so by the radiation from the sources mentioned above. Sunburn (*erythema*) is really a destruction of the cells of the skin, as is evidenced by subsequent 'peeling'. Tanning, however is quite different. It is due to a pigment formed in the cells to prevent these short waves from penetrating the skin. Exposures should be short at first, in order to allow this pigmentation to take place. This is very important in exposures to those artificial sources, which otherwise may cause severe burns and poisonous effects in a very few minutes. It has been found by medical men that, for certain ailments, gradually lengthened exposures have a beneficial action.

The eyes are extremely sensitive to ultra-violet light, even that contained in sunlight. Snow-blindness and eclipse-blindness are due to it. The shorter waves from artificial sources are still more harmful. Children's eyes are sometimes seriously affected by watching arc-welding by workmen on the streets. Any kind of glasses will protect the eyes, for ordinary glass transmits no light-waves shorter than 3300 A.

As in the case of plants, the X-rays and radium rays are destructive to animal cells, except for brief exposures such as are necessary to take photographs. These rays are used to help to destroy malignant growths. In some simple animal forms mutation has been produced by these rays.

619. Infra-red Photography. An explanation of the glorious colours seen in the west at sunset was given in § 433. It was stated that

waves from the red end of the spectrum are able to pass through the great length of atmosphere while the shorter waves of the other end are scattered or absorbed. If there is mist or haze or dust in the atmosphere the absorption effect is more decided. Indeed under such conditions all the waves of the visible spectrum are unable to pass directly through the atmosphere. They are scattered and absorbed. There may be a general illumination as when the sky is overcast in daytime, but distant objects cannot be seen distinctly.

Infra-red waves, however, may pass when red waves fail. In photographing a landscape in the usual way the outline is nearly always hazy;

FIG. 698.—Mount Rainier, Washington, U.S.A.

Photograph taken by F. S. Hogg and C. S. Beals with infra-red rays, from the Dominion Astrophysical Observatory, (elevation 750 ft.) near Victoria, B.C. Mount Rainier is 14,400 ft. high and 140 miles distant. Only a faint suspicion of the mountain could be detected by the naked eye. The strait of Juan de Fuca in the foreground here is 26 miles wide.

but if the "visible" waves are prevented from entering the camera by a suitable filter, and special plates or films sensitive to infra-red waves are used, beautifully clear pictures are obtained.

On the balloon ascension referred to in § 59, from a height of 72,395 feet the horizon 330 miles away and various physical features nearer were clearly photographed with infra-red light. Also by the same method

clearer photographs of the planets have been obtained than those given by ordinary light. In Fig. 698, is an example of infra-red photography.

620. Infra-red Signalling. Infra-red radiation may be used instead of visible light for sending military signals, and in such a way that the enemy may not be aware that there is any transmission of signals, provided the distance is not very great. A steady beam of infra-red waves is projected from one station to another and then by interrupting the beam messages in the Morse or some other code may be sent.

In a similar manner the steady beam may be projected across a channel at night. A ship moving along the channel will interrupt the beam and give a signal. The same arrangement makes an ideal burglar alarm since the beam projected across the room is quite invisible and cannot be detected.

In the above cases the apparatus which receives the infra-red waves is a photoelectric cell (§ 639) using one of the heavier alkali metals, rubidium or caesium.

621. Phenomenon of the Electric Spark. Let A and B (Fig. 699) be two knobs attached to an induction coil or an influence machine. On putting the apparatus in operation the potential of one knob rises until a spark passes between the knobs. Ordinarily one thinks simply that a quantity of electricity has jumped from one knob to the other in order to annul the difference of potential between A and B. But there is more in the phenomenon than that. As a matter of fact there is a rush across from A to B, then one back from B to A, then another from A to B, and so on, until the energy of the charge is dissipated. Thus, instead of a single spark there is a series of sparks between A and B. This has been demonstrated by photographing their images in a rapidly rotating mirror.

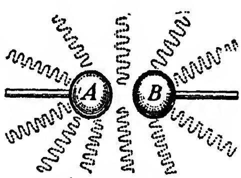


FIG. 699.—Diagram illustrating how the electric waves spread out from a spark gap.

Suppose we have a U-tube (Fig. 700) with a membrane stretched across it at D, and that the membrane is so thin that it breaks when water has been poured into the arm E to a certain height C. When the membrane breaks the water

will not come to rest at once but will oscillate up and down until the motion is stopped by the friction of the tube.

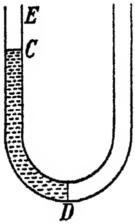


FIG. 700.—Illustrating an electric spark.

The membrane has its electrical analogy in the air-gap between the knobs A and B which breaks down when the electrical pressure across the gap becomes great enough. After this has happened the electricity surges back and forth until brought to rest by the resistance of the gap and by the loss of the energy radiated away.

Now we know that electricity in motion is always accompanied by a magnetic field, and that a reversal of current includes also a reversal of the magnetic field. A slowly alternating current passing through a wire placed over a compass needle would cause the needle to deflect first one way and then the other. A rapidly alternating current would produce a similar effect if it were not for the inertia of the needle.

In the same way the electrical surgings from knob to knob are accompanied by magnetic surgings in the surrounding space and consequently a conductor placed in this changing magnetic field should have an alternating E.M.F. induced in it.

In other words, when the discharge occurs, electromagnetic disturbances or waves are sent out in all directions into the surrounding space. Each discharge produces a train of waves.

622. Sympathetic Electrical Oscillations. When a tuning-fork is vibrated, air-waves spread out in all directions, and if a unison fork is placed not too far away (Fig. 352), the incident waves will excite easily observed vibrations in it (see § 341). It is possible to exhibit electrical resonance quite analogous to that obtained with the unison tuning-forks.

Experiment. Take two precisely similar Leyden jars A and B (Fig. 701), and let a wire run from the outer coating of A and end in a knob c' near to the knob c which is attached to the inner coating. Join these knobs to an influence machine or an induction coil.

Also connect the inner and outer coats of *B* by a wire loop *Bdef*, the portion *de* being so arranged that, by sliding it along the other wires, the area inclosed by the wire *Bdef* may be made approximately equal to that of the fixed loop on the other jar. From the inner coating of *B* bring a strip of tin-foil down to *s*, within about 1 mm. of the outer coating.

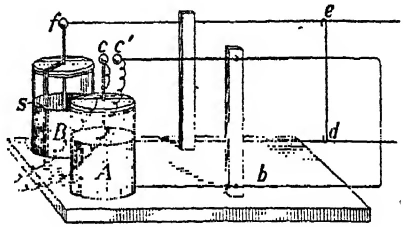


FIG. 701.—Arrangement to show electrical resonance.

Now cause sparks to pass between the knobs *c*, *c'*. Move the wire *de* until the two wire loops are nearly equal in area; there will be a little spark at *s* whenever a spark passes at *c*, *c'*. Then slide the wire *de* back or forth until the equality of the areas is destroyed; the sparks cease at *s*.

The experiment can be varied by connecting a small flash-light bulb across the gap at *s* or by inserting it in the circuit *Bdef*. The bulb will light when the circuits are in resonance.

When the spark passes at *c*, *c'* electricity surges back and forth between the outer and inner coatings of *A*, and electromagnetic waves are sent out which set up electrical oscillations in the similar circuit attached to the other jar. The natural period of the two circuits must be equal (or nearly so) for the sympathetic oscillations to be set up. One circuit is tuned to another by altering the capacity or inductance or both.

623. Electric or Electromagnetic Waves. As early as 1864 Maxwell*, by mathematical reasoning based on experimental results obtained by Faraday, showed that electric waves in the ether must exist; but they were first detected experimentally by Hertz,† a young German physicist. Hertz showed that they travel through space with the speed of light, that they can be reflected and refracted, and that they also possess other properties similar to those possessed by light-waves, but they have much greater wave-lengths.

REFERENCES FOR FURTHER INFORMATION

RAWLINGS, *Infra-Red Photography.*
MEES, *The Fundamentals of Photography.*

*James Clerk Maxwell, a distinguished British physicist. Born in 1831, died in 1879.
†Heinrich Hertz died on January 1, 1894, in his 37th year.

CHAPTER LXXXV

RADIO TRANSMISSION AND RECEPTION

624. Radio or Wireless Telegraphy. By means of electric waves it is possible to send signals from one place to another without connecting wires. A simple arrangement for doing this is shown in Fig. 702. I is an induction coil, the secondary of which is connected to the spark-gap S, the condenser C and the helix L_1 to form an oscillatory circuit similar to that used in § 622. The aerial wire A_1 is connected to one end of the helix L_2 and the ground wire G to the other.

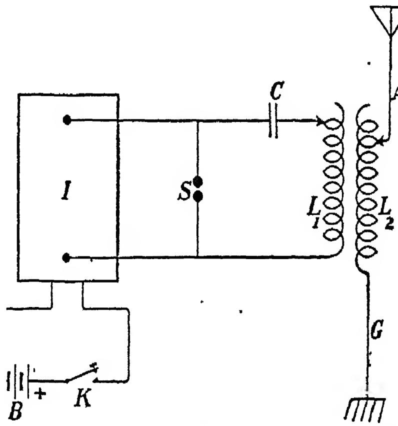


FIG 702.—Radio telegraph transmitter.

B is a battery and K a key in series with the primary of the coil. When one presses K, each vibration of the armature produces a high-tension current in the secondary of the induction coil, which charges C until the pressure becomes so great that a discharge occurs across the gap S. When this happens, high-frequency currents surge though the oscillatory circuit and induce similar high-frequency currents in the aerial-ground circuit, with the result that electromagnetic waves are sent out in all directions. Thus each vibration of the armature produces a wave-train.

The open aerial-ground oscillatory circuit produces waves of larger amplitude and is therefore a much better radiator than the closed oscillatory circuit which is used to excite it.

625. Receiving Apparatus. A simple arrangement is shown in Fig. 703. Here L_3 is a tuning coil to one end of which the aerial wire A_2 is joined, while the other end is connected to the earth. In circuit with the coil are the detector D and a pair of sensitive telephone receivers T. The electromagnetic waves travel from A (Fig. 702) with the speed of light, and on reaching A_2 they excite high-frequency alternating currents in it. The detector and receivers transform this electrical energy into audible sound. At one time a crystal of galena or silicon on which a metal point pressed (D Fig. 703) was widely used as a detector, but the **thermionic value** is much more effective.

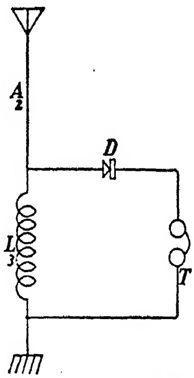
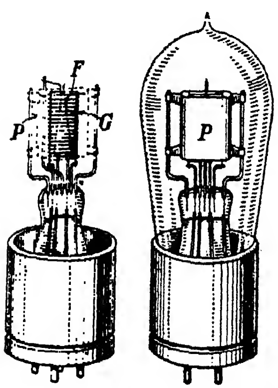


Fig. 703.—Receiving apparatus.

It should be noted that the action in this apparatus is essentially the same as when an alternating current in one coil induces an alternating current in another coil close to it. In radio work, however, the alternations are very rapid, the action extends over great distances, the circuits are tuned to one another and special apparatus must be used to detect the very weak currents induced in the receiving aerial.



704.—A thermionic valve P, G, grid; F, filament. -Outer appearance.

626. Thermionic Valve. This instrument was invented by Fleming and improved by De Forest and others. It is used both for sending and receiving radio waves and for many other purposes. It has various forms, depending on the way it is to be employed, but all embody the same essential features. One model is shown in Fig. 704. It has the form of an ordinary incandescent light bulb in which the **filament** F is lighted by a 6-volt storage battery. Sur-

rounding this filament is the **grid** *G*, consisting of a spiral of nickel wire. Around this again is a nickel cylinder *P*, called the **plate** or **anode**. The plate and grid are supported on wires sealed through the bulb and four terminal pins project through the base, two being used for lighting the filament, one for making connection to the grid and one to the plate. The action of the valve depends on the fact that an incandescent metal emits electrons freely.

Experiment. To demonstrate this action connect apparatus as shown in Fig. 705*. *A* is a 6-volt storage battery connected to the filament *F* through the variable resistance *R*. A $22\frac{1}{2}$-volt battery called the B battery has its positive pole connected to the plate *P*, while the negative pole is joined through the galvanometer *C* to the filament. When the filament is cold no current passes through *C*, but as soon as it is made incandescent the galvanometer shows a deflection because the electrons emitted by the hot filament are attracted by the positive charge on the plate. This action is equivalent to a flow of positive electricity from the positive pole of *B* to *P*, across the intervening space to *F* and through *C* back to the negative pole of the battery.

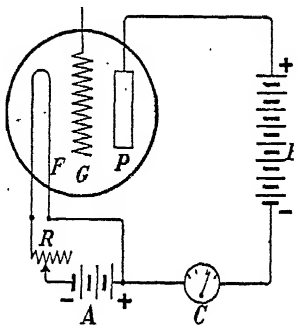


FIG. 705.—Testing the flow of current through a valve.

627. Valve Reception. A simple receiving circuit using the valve as detector is shown in Fig. 706. L_1 and L_2 are variable inductances and C_1, C_2 variable condensers used in tuning the primary (aerial-ground) and secondary circuits to the incoming waves. *T* is a pair of sensitive telephone receivers, replacing the galvanometer shown in Fig. 705. The connections are easily followed.

When the filament current is turned on, a steady stream of electrons will pass from *F* to *P*, and through the receivers, producing a steady deflection of the diaphragms. As soon, however, as the primary and secondary circuits are tuned

*For clearness the elements in the valve are shown diagrammatically.

to the incoming waves, feeble alternating currents will surge back and forth in the secondary circuit composed of L_2, C_2, G, F and connecting wires. As a result G will become charged alternately positively and negatively with respect to F. When it is charged positively it will assist P in pulling electrons from the filament, but when it is charged negatively

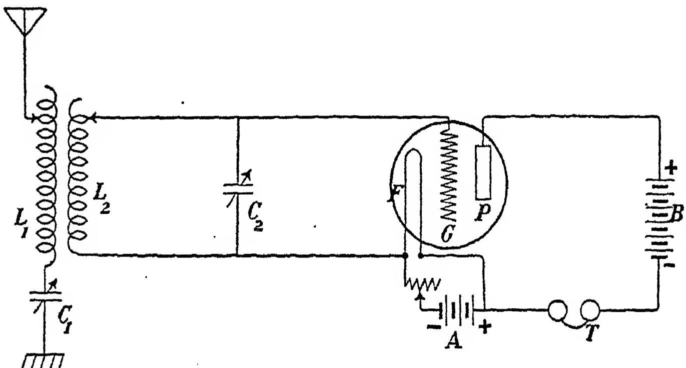


FIG. 706.—A simple receiving circuit using a valve as detector.

it will push back some of the electrons which are trying to reach P. The result is a *large increase* in the plate current when the grid is charged positively and a *smaller decrease* in the plate current when it is charged negatively. Each train of waves will therefore produce an *average* plate current greater than the normal current passing through the receivers when no waves are being received, and consequently will produce one vibration of the diaphragms.

Now each time the armature of the induction coil at the transmitting station vibrates, a discharge occurs and a train of waves is sent out. The frequency of the note heard in the receivers will therefore be the frequency of the armature of the induction coil.

The great advantage of the valve over the crystal detector lies in the fact that the current which actuates the receivers comes from the B battery and is many times stronger than the weak alternating current which sets it in operation.

The effect may be likened to a boy closing a switch which sets a large machine in motion. In the case of the crystal detector the only current available to operate the receivers is the feeble incoming current itself.

628. The Radio Tube as an Amplifier. In Fig. 707 is illustrated a radio set in which a second valve (at the right) has been added to amplify the output from the detector circuit. This latter circuit is similar to that in Fig. 706 except that the primary of a transformer S takes the place of the telephone head-set, and a grid condenser D in parallel with a high resistance E has been introduced in the grid circuit to increase the efficiency of the detector valve.

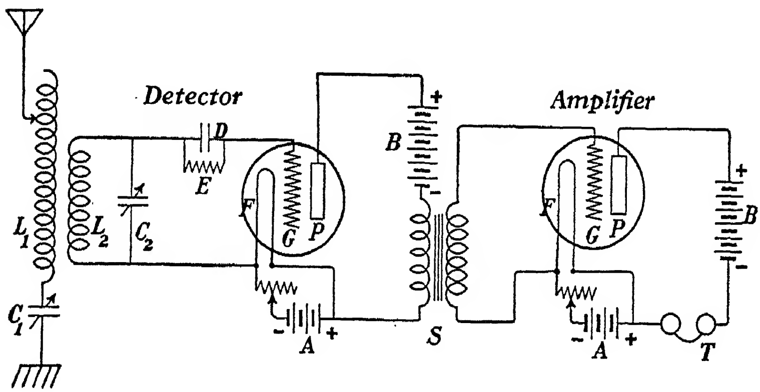


FIG. 707.—Regenerative circuit with one stage of amplification.

The terminals of the secondary of the transformer are joined to the grid and filament of the amplifier tube. By this arrangement the potential variations acting on the grid of the amplifier tube are much greater than those acting on the detector tube, and consequently the current variations in the telephones are greater than in the case of a single tube.

Amplifier units employed to strengthen the impulses delivered by the detector tube are called **audio-frequency amplifiers** and often two stages in series are used to increase further the amplification.

The above circuit may also be used to generate electric waves.

629. Wireless Telephony. In wireless telephony a valve is used to generate continuous electrical oscillations and these oscillations are **modulated** by the action of a microphone such as is used in line telephony.

A simple transmitting circuit which can be used for either continuous-wave telegraphy or wireless telephony is shown in Fig. 708. L_1 and L_2 are inductances of about 36 and 80 turns wound on forms 4 and 3 inches in diameter. C_1 is a $\frac{1}{4}$ m.f. condenser and C_2 a variable 0·001 m.f. condenser. P and S are the primary and secondary coils of a telephone transformer. M is the microphone operated by the same battery which is used to light the filament. The high-tension generator, which should have an E.M.F. of about 350 volts when a 5-watt valve is used, is connected to E and F. A is a hot-wire ammeter placed in the aerial circuit.

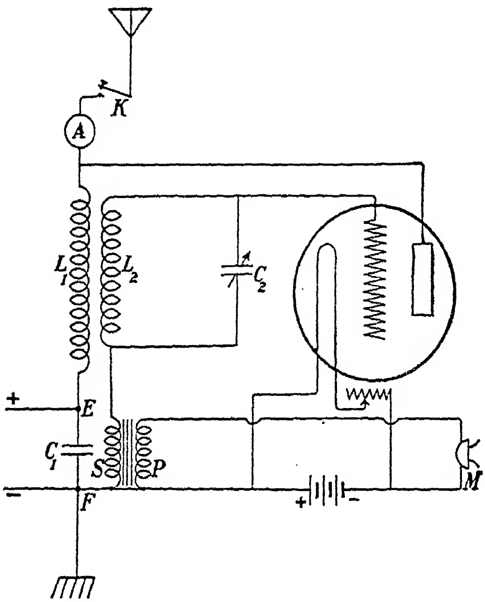


Fig. 708.—Transmitting circuit for continuous-wave telegraphy or wireless telephony.

In telephoning, the key K is kept closed and the circuits are tuned until the ammeter registers a satisfactory current. The sound to be transmitted is then produced in front of the microphone.

By this means the potential of the grid is made to vary in accordance with the sound waves falling on the microphone and, consequently, the outgoing continuous wave-train has impressed on it electromagnetic variations corresponding to the sound waves.

630. Modern Radio Receivers. Radio receiving sets at the present time operate from the A.C. mains in the house without the use of batteries.

A transformer with low-voltage windings in the secondary supplies the current required to heat the filaments of the radio valves, while some high-voltage windings on the same transformer supply the E.M.F. for the plate circuits, and the supply is changed from A.C. to D.C. by means of radio tubes used as rectifiers.

Further details cannot be given here.

631. Short Wave Transmission. In Fig. 709 is shown a circuit suitable for transmitting short waves having lengths from 40 to 200

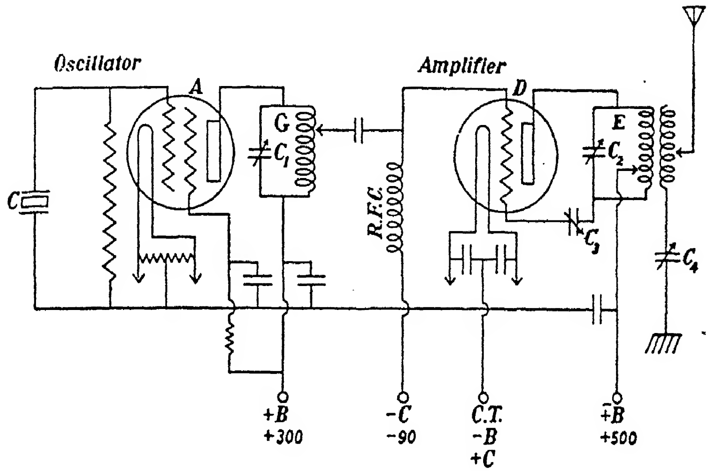


FIG. 709.—Short-wave transmitting circuit with one-stage amplification.

metres, *i.e.*, with frequencies from 7·5 to 1·5 megacycles.* It is known as a crystal-controlled circuit. A thin plate C of crystalline quartz, with faces ground accurately flat and parallel to each other, is mounted between two metal plates. The crystal plate has a natural period of oscillation of its own which depends on its thickness and the plane in which it is cut from the crystal. This plane is always cut parallel to the optic axis (the long axis of the crystal) and for frequencies above 400 kc. a plane is chosen which is parallel to lines joining the opposite edges of the crystal. For a thickness of 1 mm. the frequency is 2 megacycles $= 2 \times 10^6$ cycles. A plate of the size and thickness of a 10-cent piece gives about 1800 kc. The frequency of the circuit depends almost entirely upon the crystal and not directly upon the coils and condensers. Fluctuations in the voltage of the supply heating of valves or a swinging antenna will not affect the frequency as they do in self-controlled regenerative circuits. The frequency may be doubled by using the first harmonic of the crystal.

The oscillator circuit consists of the valve A, the crystal C and the resonance or "tank" circuit G. The rest of the diagram shows one stage of amplification (§ 629), using the valve D, the tank circuit E, and the

*This relation is obtained from the universal formula $v = nl$ (§ 294). In the present case $v = 3 \times 10^8$ metres per sec., and if $n = 2000$ kc. $= 2$ megacycles $= 2 \times 10^6$ cycles, then $l = 150$ metres. The thinner the plate, the higher the frequency.

antenna circuit. The coil *RFC* is the radio-frequency choke. Condensers C_1, C_2, C_3 and C_4 are all variable, while the rest are fixed mica condensers. The condenser C_3 is needed because both the grid and plate circuits of valve *D* are tuned to the same frequency, and the valve would oscillate of its own accord unless prevented. The small transformers used for heating the filaments of the valves are not shown, nor the power transformer necessary to give the 500 volts for operating the set. This power must also be rectified, *i.e.*, changed from an alternating to a direct current. The negative sides ($-B$) of both high potential circuits are connected to the centre tap (*C.T.*) of the transformer, and $+ C$ and $- C$ is the grid bias of 90 volts. If the circuit is to be used for radio broadcasting, a circuit containing a microphone and inductance similar to the lower part of Fig. 708 is included.

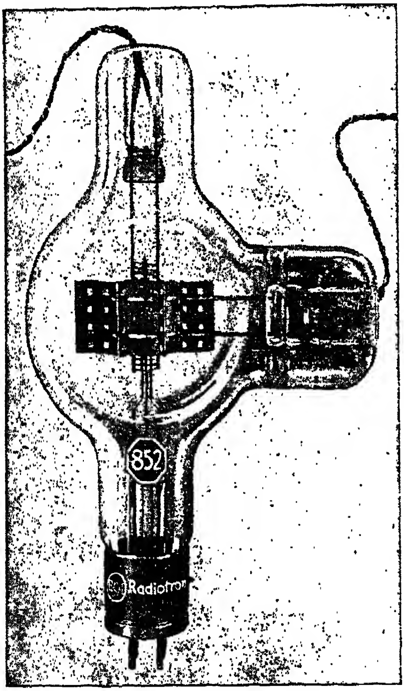


FIG. 710.—A triode short-wave transmitting and receiving valve.—(*Courtesy of R.C.A. Manufacturing Co., Harrison, N.J.*)

In short wave circuits the inductance and capacity must be small in order to increase the frequency, *i.e.*, to decrease the wave-length. The relation between these quantities is $l = 1885 \sqrt{LC}$, where l is in metres, L in microhenries and C in microfarads, but the explanation of these quantities is beyond the scope of this book.

The wire leads must be short, and specially constructed valves, in which the leads are separated from each other, are used. The valves, coils, etc., are all very small compared to ordinary circuits. In Fig. 710 is shown one type of valve used for short wave transmission and reception. Observe how the leads come out. A pentode receiving valve known as No. 47 is suitable for *A* and a triode No. 45, or better No. 210, for *D*.

632. Radio Transmitters for Exploring the Air. In response to the urgent demand for information regarding the condition of the atmosphere at various heights in order to provide dependable weather forecasts for air navigation, small short-wave radio transmitters have been devised. These are usually carried aloft by small balloons and automatically send out, two or three times a minute over a period of three hours, signals which are recorded on a strip of moving paper on the ground. The records when interpreted give the temperature, pressure and humidity at various heights. In one type of construction the instrument is contained in a box of $\frac{1}{4}$-inch balsa wood having outside dimensions $1\frac{1}{2}$ x $1\frac{3}{4}$ x $3\frac{1}{4}$ inches and weighing one pound. The antenna is the wire by which it is suspended from the balloon and the wave-length is 68 metres.

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CHAPTER LXXXVI

X-RAYS, PHOTOELECTRICITY, RADIOACTIVITY

633. Passage of Electricity through Gases. In investigating this subject the gas is usually contained in a glass tube (Fig. 711) into the ends of which platinum wires are sealed.

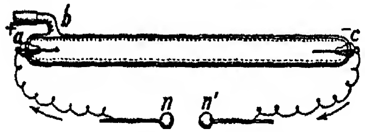

FIG. 711.—Arrangement to study the passage of electricity through a gas.

The terminals n, n' of an induction coil are joined to a and c, the electrodes of the tube. Let the electricity enter the tube at a and leave at c; these are, then, the anode and the cathode, respectively. Sometimes the electrodes have aluminium discs upon them. By connecting a side tube b to a good air-pump the air can be exhausted from the tube.

At first, when the air in the tube is under ordinary atmospheric pressure, the discharge passes between n and n', but as the pressure is reduced, it begins to pass between a and c; and as the exhaustion is continued some very beautiful effects are produced. The colour depends on the kind of gas in the tube. This effect is seen in our brilliant street signs.

If, however, the exhaustion is pushed still further, until the pressure within the tube is about one millionth of an atmosphere, phenomena of a different class are produced. As Sir William Crookes was the first to study these phenomena in great detail, these very highly exhausted tubes are known as Crookes tubes.

From the cathode something is shot off which travels within the tube in straight lines and with great speed. This has been shown to consist of very small particles charged

with negative electricity, and the streams of these particles are known as **cathode rays.**

634. Nature of Cathode Rays. That cathode rays really consist of streams of rapidly moving electrons can be demonstrated by the apparatus shown in Fig. 712. In the Crookes tube *AB* is a long vertical screen *CD*, coated with zinc sulphide. The end at *C* is bent at right angles to the screen and has a narrow horizontal slit cut in it. The middle line of the screen makes a small angle with the axis of the tube.

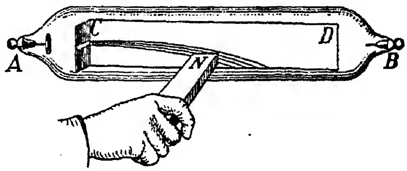

FIG. 712.—Cathode rays are deflected by a magnet.

When the electrodes are joined to an induction coil the cathode rays pass through the slit and glance along the screen, producing fluorescence in a straight line. If now the *N*-pole of a magnet is brought close to the side of the tube, the streak of light is deflected in the same way that a wire bearing a current would be deflected. We therefore conclude that a current is passing through the tube in the form of a stream of electrons.

Exercise. Using the right-hand rule (Fig. 619) determine the direction in which a stream of negatively-charged particles shot from *C* should be deflected when the magnet is held as shown in Fig. 712.

635. Röntgen Rays. In 1895, Röntgen, a German physicist, while experimenting with Crookes tubes, discovered a new kind of radiation which he called X-rays. In Fig. 713 is shown a X-ray

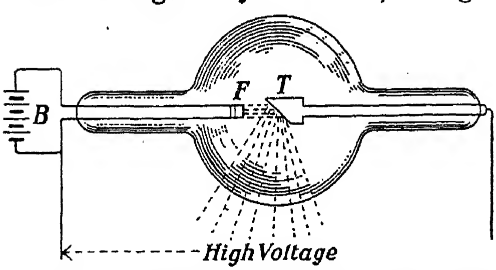

FIG. 713.—A Coolidge X-ray tube. The high voltage is supplied by a transformer.

tube. The filament in the cathode at F, heated by the battery B, gives out a stream of electrons which are driven with high velocity against the tungsten anode T (often called the target) by a potential of 50,000 volts or more supplied by the secondary of a suitable transformer. When the electrons strike the target (or any other solid) X-rays are pro-

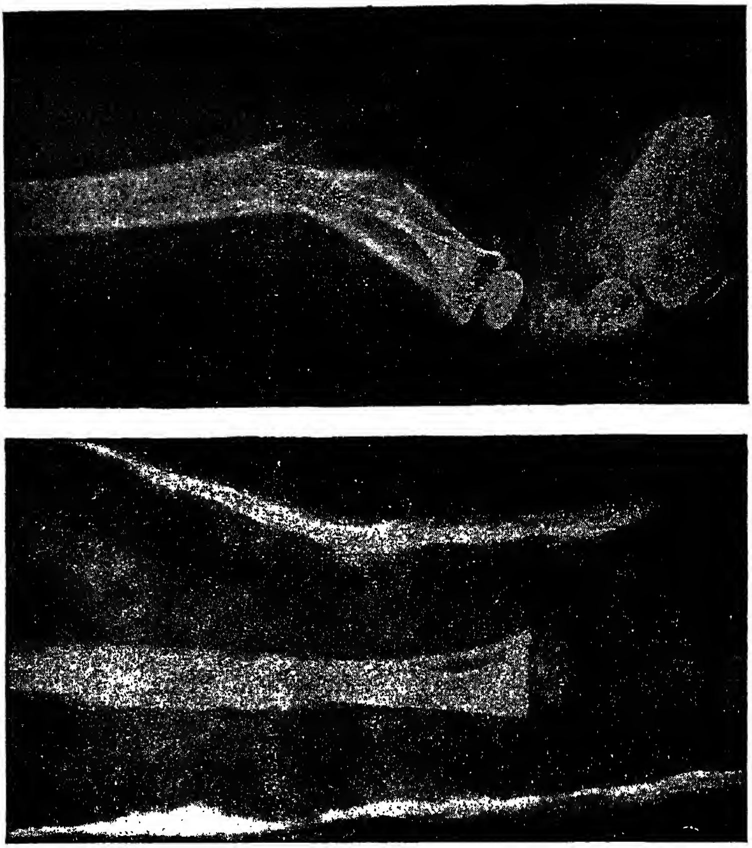

Fig. 714—X-ray photographs of the broken left arm of a four-year old child.

Above.—Taken on January 28, 1937. Note that both bones are broken. The photograph shows also the bones of the wrist and a part of the hand, the thumb being separate from the others.

Below.—Taken on January 30, two days later, through the plaster cast on the arm.

(*Photographs taken at the Hospital for Sick Children, Toronto.*)

duced which spread out as shown in the figure, easily passing through the walls of the tube.

636. Photographs with X-Rays. The X-rays can affect a photographic film just as light does. They can also pass through substances quite opaque to light, such as wood, cardboard, leather, flesh, but they do not so easily penetrate denser substances such as bones, lead, iron and brass. If a photographic film is held behind a portion of the human body which is being exposed to the X-rays, the rays easily pass through the flesh but are considerably hindered by the bones. Consequently when the film is developed, that part which was behind the flesh is much more blackened than that behind the bones. When a print is made from the 'negative' we obtain a shadow picture like those in Fig. 714.

In place of a photographic plate we may use a paper screen coated with crystals of barium-platino-cyanide. When the rays fall upon this, it shines with a peculiar yellow-green shimmering light. It is said to **fluoresce.** The shadow of an opaque body is clearly seen by this light.

637. Cosmic Rays. There is another radiation, which comes from beyond the earth and has been called Cosmic rays. It is probably of the same nature as X-rays, but as it is much more penetrating it is thought to be of much shorter wave-length. It passes freely through buildings and other things on the earth's surface. This radiation was first detected about 1904 by Rutherford and Cooke at Montreal, and McLennan and Burton at Toronto, by different methods. More recently investigations have been carried on in different parts of the world by Regener of Germany, Millikan of California and Compton of Chicago.

638. Conduction of Electricity through Air. It is believed that electricity is conducted through a gas much as it is through a liquid. The latter was explained in § 515.

Let C and D (Fig. 715) be two parallel metal plates placed a few centimetres apart, and let C be joined to one pole of a battery, the other pole being joined to earth. E is an electrometer. This is a delicate instrument which measures the electrical charge given to it. First, suppose the tube T not to be in action; the needle of the electrometer will be at rest. Then let the tube be started, and let the X-rays pass into the air between the plates C and D. At once the electrometer begins to receive a charge, showing that electricity has passed across from C to D and thence by the wire w to the electrometer.

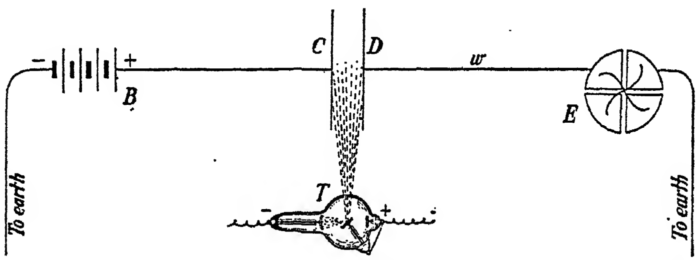

FIG. 715.—An arrangement to exhibit the conduction of electricity by air. The X-rays *ionize* the air.

When the X-rays pass through a gas, they cause the molecules of the gas to be broken up into positively and negatively charged carriers of electricity which, as in the case of a liquid, are called **ions.** This process is called **ionization.** When a molecule is ionized, it is broken up into two ions, the electrical charges of which are equal in magnitude but of opposite sign. The positive ions are repelled from C to D and the negative ions are attracted by the plate C. In this way the electricity is transferred from C to D.

639. Photoelectric Effect. An instrument for measuring illumination by means of an electric current generated when light falls on a thin layer of selenium was described in § 369. This is one of many examples of the production of electricity directly from light.

When light of suitable wave-length falls upon a clean metal surface a cloud of electrons is emitted by the surface. In the case of most metals the proper wave-lengths to be used are in the ultra-violet, but for potassium any waves shorter than 5500 A. (which is in the yellow) will produce the effect. For polished platinum the waves must be shorter than 1962 A., which is far into the ultra-violet. The number of electrons emitted per second is proportional to the intensity of the light.

In practice the metal (say, potassium) is deposited on a portion of the inner surface of a glass bulb (*A*, Fig. 716) which is either highly evacuated or contains a slight amount of an inert gas such as argon. Facing the potassium (the cathode) is a wire ring *B* (the anode) and wire leads from the two electrodes come through the glass and are put in circuit with a battery, the anode being joined to the positive pole. In darkness no current flows in the circuit, but when light is projected through the clear wall of the bulb upon the potassium a current is at once set up. When the light falls on the potassium electrons are emitted from the surface of the metal, and, assisted by the voltage of the battery, they rush over to the anode. The current thus set up is very small and ordinarily must be amplified to be utilized.

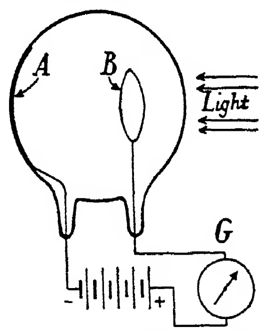

FIG. 716.— Diagram of a photoelectric cell. *A*, potassium on inner surface of bulb; *B*, ring anode; *G*, galvanometer for detecting a current.

This instrument is called a **photoelectric cell.** It is very important from a theoretical point of view, and it has many practical applications. If a steady beam of light passes across passage to the kitchen of a restaurant and falls on a photoelectric cell, the electric current can be arranged so that when a waiter interrupts the light the door opens. The cell has been adapted to count passing automobiles, to

turn lights on at night and off in the morning, to measure the light from the stars, and it is an essential part of the "talking movie" and in television.

640. Radioactivity. In § 164 is a brief outline of the electrical structure of matter. An atom of a substance consists of a central part called the nucleus and outside of it is a definite number of electrons. The nucleus contains one or more protons and some electrons, all bound together in some mysterious way. It is the important part of the atom. If it is altered the atom becomes a quite different atom. This occurs spontaneously in some of the heavier atoms, and the process is called **radioactivity.**

In 1896 Becquerel, a French physicist, discovered that uranium and its compounds emitted a radiation which could pass through opaque materials and fog a photographic plate. Madam Curie of Paris, after a very laborious chemical research, succeeded in separating from several tons of pitchblende a few milligrams of a substance more than a million times as powerful as uranium. To this substance the name **radium** was given.

Radium has some of the characteristics of X-rays, it is of great value in scientific investigations and has numerous uses in medicine. It is extremely scarce and consequently very expensive. For some years the chief source was the Belgian Congo, but recently mines containing radium were discovered on the east shore of Great Bear Lake, N.W.T. (see Plates facing pages 288, 636, 637). The ore is shipped 4,000 miles to the refinery at Port Hope, Ont. The process of refining is long and tedious, the radium concentrates passing through twenty-two stages of precipitation, and one gram of radium is obtained from 6½ tons of ore.*

*The refinery began operations in 1933 and by November 16, 1936, one ounce of radium had been produced (1 oz. = 28.3 gm.) "The price is about $25,000 per gram, which is less than half its previous price." The whole story of this development is full of romance. See *Canadian Geographical Journal*, March, 1937.

THE REFINING OF RADIUM, PORT HOPE, ONT.

The last stages in the refining of radium consist of twenty-three processes of fractional crystallization. During these stages the infinitesimal amounts of radium are slowly coaxed away from the barium which had been added previously to enable the workers to keep track of the radium. In the stage pictured above the radium-~~barium crystals~~ are being scraped from the surface of quartz bowls.

(Photograph from Eldorado Mines)

RADIUM IN A FLASK (ABOVE) AND IN A GLASS TUBE (BELOW)

In the flask are radium-barium crystals containing more than a gram of radium and worth $25,000—which is less than half of its price before the discovery of radium in Canada. This amount of radium is the outcome of the labour of 93 men for 2 weeks in the mines at Great Bear Lake and of 48 more workers for another 2 weeks in the refinery at Port Hope.

In the tube, which is about the size of a match, is one-tenth of a gram of radium about one minute old. The material shown is about 90% radium. It will later be encased in lead to protect surrounding objects from its radiation.

(Photographs from Eldorado Mines, Mr. Gilbert La Bine, President)

It is thought that in the course of ages the heavier atoms may have been built up from the lighter ones by the addition of further parts to the nucleus, and that as the structure became heavier and more complex a stage was reached at which the nucleus became unstable and began to "blow up." This explosion of the nucleus is the cause of radioactivity. It occurs with singular regularity. Of all the atoms in (say) a gram of uranium, a fixed and definite fraction will explode every second. The explosions can be made visible in a little instrument called the **spinthariscope**. In the explosion, however, the nucleus does not fly "all to pieces." One or two of the pieces are thrown out with great violence, and the atom changes over to a new atom of a different substance of lighter weight and somewhat simpler structure. Later on this new atom may explode and change by another step into an atom of a still simpler kind. Thus we have a **radioactive** series of atoms. Three such series are known. One of them begins with uranium and includes over a dozen changes, one of the atoms formed being radium. Radium in turn breaks down by several more steps until the process ends with an atom of lead.

641. Three Kinds of Emission. In radioactivity the parts of the nucleus which are thrown out are of two kinds, **alpha particles** (helium nuclei) and **beta particles** (electrons). The name 'ray' was at first used for both of these, but we now know they are both material particles. The alpha particles are easily stopped. A sheet of aluminium foil $\frac{1}{20}$ mm. thick will cut them off. The beta particles are much more penetrating.

There is one other kind of emission during the radioactive change, namely, the **gamma rays**. These are true rays, *i.e.*, waves, of the nature of X-rays but of shorter wave-length and still more penetrating. The use of radium, or of any other radioactive substance, for the treatment of disease depends largely on the volume of gamma rays which the substance emits in a given time. A substance whose atoms break down rapidly (short-lived substance) of course emits more particles and gamma rays per second and is more useful for radioactive treatment. Much of the effect obtained by the use of radium really comes from the atoms of other substances formed from radium and mixed with it. Some of these substances decay very rapidly.

642. Nature's Unchanging Laws. In nature things happen according to unchanging laws and the contemplation of these laws, which is the study of science, should give us confidence to live our lives in the natural world. Human institutions, including governments, fail and disappoint us, but these laws are never broken or repealed. On the other

hand *we* may not violate them without suffering unpleasant consequences. Science moves forward from one triumph to another because of the discovery of the way in which nature works. Doubtless many wonderful discoveries lie in the future to be brought to light by patient study and careful experimentation.

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Lord Rutherford, *The Newer Alchemy.*
H. S. Allen, *Photo-electricity.*
*Rather advanced for students

REVIEW PROBLEMS

Measurement

1. From Amiens to Paris the distance is 112 km. Express this in miles.

2. The reading on the speedometer of an English bus is 40 miles per hour. What would be the reading in km. per hour?

3. French field guns have a bore of 75 mm.; British eighteen-pounders measure 3·3 in. Express the difference in cm.

4. The reading on a mercury barometer was 75·28 cm., and an aneroid barometer alongside it registered 30·24 in. Assuming that the former was correct, find the error in the latter in inches.

5. Express the difference in pounds between a metric ton (1000 kg.) and a ton of 2000 pounds.

6. Find the difference in cu. in. between 5 Imperial gallons and 6 U.S. gallons, and hence show that 1 Imp. gal. = 1·2 U.S. gal. (approximately). If an Imp. gal. of gasoline sells for 18 cents plus government tax 6 cents, what should be the price, at the same rate, of a U.S. gal. with tax 5 cents?

7. Find the specific gravity of an alloy consisting of 4 parts by volume of copper to 3 parts of zinc. (Assume no shrinkage or expansion.)

8. Calculate the weight in kg. of a litre of (a) ethyl alcohol, (b) mercury, (c) chloroform.

9. Find the weight of the water in a swimming tank 75 x 25 x 8 ft. in dimensions (a) in tons (b) in kilograms. (Take 1 cu. ft. water = 62·4 lb.)

10. An oak beam measures 20 x 2 x 0·5 ft. Calculate its approximate weight in pounds.

Mechanics of Fluids

1. What pressure will be produced at a tap when the vertical height of the water in the reservoir is 100 ft. above the level of the tap? (1 cu. ft. water weighs 62·4 pd.)

2. If the diameters of the cylinders of a hydraulic press are in the ratio 1:8, what will be the mechanical advantage of the press?

3. A body whose specific gravity is 8·3 weighs 124·5 gm. What will it weigh when immersed in water? What is its volume?

4. A balloon contains 2000 cu. m. of a gas whose density is ·000091 gm. per cc. If the density of air is ·001293 gm. per c.c., find the total weight which the balloon will lift.

5. When the barometer is 30 in. high find the air pressure in grams per sq. cm. and pounds per sq. in. (1 in. = 2·54 cm.; 1 kg. = 2·2 lb.; s.g. of mercury = 13·6.)

6. A litre of air at 5°C. and under a pressure of 76 cm. mercury weighs 1·289 gm. What volume of air at the same temperature will weigh 1·289 gm. when under a pressure of 95 cm. mercury?

7. A certain mass of gas occupies 200 cu. ft. when the pressure is 20 pounds per sq. in. Under what pressure will the same mass of gas occupy 150 cu. ft.?

8. By a suction pump water has been raised 24 ft. above the level of the water in the well. If the diameter of the piston is $3\frac{1}{2}$ in. find the force which must be exerted on the piston rod to raise the piston. (1 cu. ft. water weighs 62·4 pd.)

9. At a garage a motor car is raised on a platform attached to the upper end of a long vertical piston, which descends into a cylinder in the ground, by water admitted to the cylinder. If the car and platform weigh 3300 pounds and the diameter of the piston is 10 in., find the pressure of the water required, neglecting friction.

10. What is the total force against a vertical lock-gate which is 20 ft. wide when the water in the lock is 18 ft. deep? If a ship weighing 1500 tons moves into the lock and the depth of the water remains the same, what will be the force on the gate?

Mechanics of Solids

1. With what velocity must a body be projected vertically upward in order that it may rise 3600 ft.? ($g = 32.$)

2. A body is projected horizontally with a velocity of 30 ft. per sec. from the top of a cliff 144 ft. above the level of a lake. How far will the body travel horizontally before striking the lake?

3. A weightless rod 12 ft. long has masses of 20 and 60 lb. attached, one at each end. Find the position of the centre of gravity.

4. Two tugs pull on a vessel with forces of 1000 and 2400 pd. and their cables are at right angles to one another. Find the resultant pull on the vessel.

5. What force acting on a mass of 10 gm. for 5 sec. will produce a velocity of 100 cm. per sec.?

6. A body starts from rest and moves 1000 cm. in 20 sec. under the action of a 50-dyne force. Find the mass of the body.

7. How many gallons of water can a 2 h.p. engine raise per hour from a well 20 ft. deep.?

8. The engines of a steamship when developing 160,000 h.p. drive the ship at the rate 30 m.p.h. Calculate the friction (in pounds) exerted by the water opposing the motion of the ship.

9. The cylinder of a steam engine has an internal diameter of 5·6 inches and the average pressure of the steam during the stroke is 80 pounds per sq. in. If the length of the stroke is 10 in., find the work done per stroke in foot-pounds.

10. The load on a wheelbarrow is 270 lb. and can be considered as acting at a point $2\frac{1}{2}$ ft. from the axle of the wheel. What upward force must a man exert on the handles, which are $4\frac{1}{2}$ ft. from the axle, when pushing the barrow?

Expansion by Heat

1. A brass rod at 15°C. is 62·00 cm. in length, and when raised to 55°C. it is 62·05 cm. in length. Find the coefficient of linear expansion.

2. A horizontal glass tube of uniform bore is closed at one end; the other is open to the air. A drop of mercury which slides easily along the tube serves to confine a part of the air in the tube. If this drop is 20 cm. from the closed end of the tube when the temperature is 10°C., how far will it move if the temperature be raised to 60°C.?

3. A mass of gas at 12°C. and under 760 mm. pressure occupies 150 c.c. If the temperature is raised to 50°C. and at the same time the pressure falls to 750 mm., calculate the new volume occupied by the gas.

4. A glass bottle has a capacity of 100 c.c. and is filled with mercury at 0°C. Neglecting the expansion of the bottle, what weight of mercury will escape from the bottle if the temperature is raised to 100°C.?

5. A certain mass of gas occupies 208 c.c. at 10°C. At what temperature will it occupy 226 c.c., if the pressure remains constant?

Specific Heat

1. Four beakers each contain 200 gm. of water, the temperatures being respectively 5°, 10°, 15°, 20°C. The water is all poured into an aluminium vessel at 15°C., weighing 50 gm. (sp. ht. 0·20). Find the resulting temperature. Find also the water equivalent of the aluminium vessel.

2. Find the temperature of equilibrium when 500 gm. of lead at a temperature of 98°C. is dropped into 300 gm. of water at 16°C., contained in a copper calorimeter weighing 100 gm.

3. The specific heat of sulphur is 0·2. If 1000 gm. of it at 80°C. are dropped into 200 gm. of water at 20°C. what will the resulting temperature be?

4. Find the resulting temperature of the mixture of 30 gm. of water at 40°C. with 50 gm. of alcohol at 60°C. (sp. ht. of alcohol, 0·60.)

5. On pouring 120 gm. of a liquid at 100°C. into 300 gm. of water in a cup whose water equivalent is 8 gm. the water and cup rise from 13 to 27·5°C. What is the specific heat of the liquid?

Latent Heat

1. An iron ball of mass 800 gm. is heated to 100°C. and dropped into a cavity in a block of ice which is just at the melting point. If 113 gm. of water result from the melting of the ice find the specific heat of iron.

2. A piece of ice weighing 120 gm., at 0°C., is dropped into 200 gm. of water at 60°C. Find the temperature of the mixture when all the ice is melted.

3. A piece of ice is placed in water contained in an aluminium calorimeter. Calculate the heat of fusion from the following data:

Mass of calorimeter, 25 gm.; specific heat of aluminium, 0·20 gm.; mass of water, 200 gm.; initial temp. of water, 20°C.; mass of ice 22 gm.; final temp. of water, 10·3°C.

4. Find the temperature resulting from the mixture of 125 gm. of ice at 0°C. with 400 gm. of water at 40°C. contained in a copper vessel weighing 100 gm.

5. If 20 gm. of ice at 0°C. are dropped into 120 gm. of water at 60°C., find the temperature after all the ice has melted.

6. What weight of steam at 100°C. must be passed into 2 kg. of water at 12°C. in order that the resulting temperature may be 80°C.?

7. How many calories of heat are needed to change 1250 gm. of ice at −20°C. to steam at 100°C.?

8. How many B.T.U.'s are required to melt 100 lbs. of ice and to change the resulting water to steam at 212°F.?

9. The condensation of 50 gm. of alcohol vapour without change of temperature produces sufficient heat to raise the temperature of 666 gm. of water 15 C. deg.; find the amount of heat necessary to vaporize 1 gm. of alcohol.

10. Into 2 kg. of water at 20°C., 100 gm. of steam at 100°C. are passed. Find the final temperature of the mixture.

Velocity of Sound

1. From a high elevation you estimate the time elapsing from seeing the steam come out of the whistle of a ship until hearing the sound and you make it 8 sec. How far away is the ship? (Temp. 15°C.)

2. How far off is a storm when there is an interval of 10 sec. between a flash of lightning and the thunder, the temperature being 18°C.?

3. A tuning fork has a frequency of 256 vibrations per sec., and the velocity of sound is 1120 ft. per sec. Find the wave-length of the sound produced.

4. Find the wave-length in air at 20°. produced by a fork vibrating 400 times per sec.

5. In an experiment with Kundt's tube the tube was filled with oxygen and the nodes were found to be 4 in. apart. If the frequency of the rod was 1500 vibrations per sec., calculate the velocity of sound in oxygen.

Vibrating Strings

1. A string 80 cm. long vibrates 320 times per sec. when the tension is 40 kg. What will be the frequency when the tension is 160 kg.? What length of string under the initial tension would produce the same frequency?

2. A wire 96 cm. long makes 128 vibrations per sec. under a certain tension. What must the length become if the frequency is to become 512 per sec., the tension remaining constant?

3. An aluminium wire and another wire of the same length and diameter are stretched on a sonometer, and are in unison. If the density of the second wire is four times that of the aluminium wire, and if the tension of the aluminium wire is 20 pounds, what must be the tension of the other wire.

4. Compare the frequencies of two steel wires, the first 100 cm. long, 1 mm. in diameter and under a tension of 15 pounds.; the second 80 cm. long, $\frac{1}{2}$ mm. in diameter and under a tension of 60 pounds.

5. A stretched string gives middle *C* when plucked. A bridge is placed at the middle of the wire while at the same time the tension is made four times what it was. What note will be produced by either half of the wire?

Resonance; Organ Pipes

1. A tuning-fork makes 512 cycles per sec., and is in resonance with a closed tube 16·5 cm. long. Find the velocity of sound in air.

2. When the velocity of sound is 1120 ft. per sec., how long is a closed organ pipe whose first overtone has a frequency of 288 vibrations per sec.?

3. Find the length of an open organ pipe whose fundamental is in unison with a fork making 320 vibrations per second. (Temp. 20°C.)

4. An open organ pipe is 60 cm. long. What is the wave-length of its fundamental? If the velocity of sound is 342 metres per sec., find the frequency of the note.

5. An open organ pipe is 80 cm. long. What must be the length of a closed pipe which gives the octave above?

Shadows

1. In a partial eclipse of the sun the images of the sun seen through the leaves of a tree are crescent-shaped. Explain why.

2. A man whose height is 6 ft. observes that his shadow is 10 ft. long and the shadow cast by a tower is 250 ft. long. How high is the tower?

3. A pin-hole camera is 10 in. long and has a 4 x 5 in. plate. How far from a building 80 ft. high by 100 ft. long must the camera be held in order that the image may just cover the plate?

4. If the sun's rays make an angle of 45° with the horizon, how long will be the shadow cast by a tree 80 ft. high?

5. If the velocity of light is 186,000 mi. per sec., and that of sound 1120 ft. per sec., how long would it take each to travel a distance equal to the circumference of the earth (25,000 m.)?

Illumination

1. Compare the illumination produced by a 10 c.p. lamp at 200 cm. distance with that produced by a 25 c.p. lamp at 100 cm. distance.

2. A 16 c.p. lamp is placed one metre from a 25 c.p. lamp. Where must a screen be placed between them in order that its sides shall be equally illuminated.

3. An arc lamp 100 ft. from a screen illuminates it as much as a 16 c.p. lamp 8 ft. away. What is the c.p. of the arc?

4. A body 50 ft. from a luminous point is moved 20 ft. nearer the point. Compare the illumination of the body in the two positions.

5. The mean distance of the planet Mercury from the sun is 36,000,000 mi., that of the earth is 93,000,000 mi. Compare the intensity of the light (and heat) received from the sun by a square foot on Mercury with that on a square foot of the earth.

Plane Mirrors

1. A piece of white blotting-paper reflects most of the light which falls on it. Why can it not be used as a mirror?

2. A candle is 36 in. in front of a plane mirror and the mirror is moved, parallel to itself, until 12 in. from the candle. How far did the image move?

3. A narrow lane between high walls runs eastward into a highway running north and south, and a large plane mirror is placed at the junction so that a person driving along the lane can see a car coming from the north. Make a diagram to show how the mirror should be set.

4. A ray strikes a plane mirror obliquely and the mirror is turned so that the new reflected ray is at right angles to the former reflected ray. Find the angle through which the mirror has been turned.

5. How must a ruler be held in front of a plane mirror in order that its image and itself may form two sides of an equilateral triangle?

Curved Mirrors

1. Distinguish between a real and a virtual image.

2. Describe two methods for finding the focal length of a concave mirror.

3. State the Laws of Reflection from curved mirrors.

4. A concave spherical mirror has a radius of curvature of 30 cm. An object is placed 75 cm. from the mirror. By means of a diagram locate the image. Is it real or virtual, erect or inverted? What is the magnification?

5. The filament of an electric lamp is 8 cm. high. The lamp is lighted and placed so that the filament is 50 cm. from a concave mirror. The image is caught on a screen which is 20 cm. from the mirror. How high is the image?

6. An object 4 cm. high is held 15 cm. in front of a convex mirror of radius 60. cm. Find the position, nature and size of the image.

7. An object 3 cm. high is placed 20 cm. from a concave mirror whose radius of curvature is 24 cm. Find the position, size and nature of the image.

8. A candle is held before a convex mirror of radius 12 in. (*a*) 8 in., (*b*) 16 in., from the mirror. Find the position and size of the image in each case.

9. An electric lamp stands on a table and is 8 ft. from a wall. By means of a mirror you produce an image of the lamp on the wall which is 3 times as large as the lamp. What kind of mirror is it? What is its radius of curvature? Is the image erect or inverted?

10. Would an image produced by a concave mirror show any colour effect? Give one advantage of a reflecting telescope (§ 450) over a refracting instrument (§ 449).

Refraction—Lenses

1. Find the velocity of light in water and in Canada balsam, if the velocity in air is 186,000 miles per sec. (See table § 401.)

2. Find the angle of refraction when light passes from air to glass, the angle of incidence being 25° and the index of refraction being 1·5.

3. A projection lantern throws upon a screen an image of a picture 2 x 3 in. in size on a lantern slide placed 10 in. from the projecting lens. If the screen is 30 ft. from the lens, find the size of the image.

4. A lamp is 120 cm. from a screen. Where must a lens be placed in order to throw upon the screen an image of the lamp five times as high as the lamp itself? What must be the focal length of the lens?

5. Calculate the power and focal length of a compound lens composed of a converging lens having a focal length of 10 cm. and a diverging lens whose focal length is 25 cm.

6. The focal length of a converging lens is 15 cm. An object 2 cm. long is placed 10 cm. from the lens. (*a*) Is the image real or virtual? (*b*) How far is the image from the lens? (*c*) What is the size of the image?

7. If the index of refraction from air to rock salt is 1·544, find the critical angle for rock salt. (Make a careful diagram and measure the angle.)

8. Light passes through a 60° prism made of glass having an index 1·52. By means of a diagram calculate the angle of deviation when the angle of incidence is $49\frac{1}{2}°$.

9. A camera having a simple lens is focussed upon a man 6 feet tall, standing 12 ft. from the lens. If the film is 6 in. from the lens, compute the size of the image. Find also the focal length of the lens.

10. The focal length of a telescope is 6 ft. The lens is composed of two lenses, one converging and the other diverging. If the focal length of the former is 30 in., find that of the latter.

Magnetism

1. A rod of soft-iron is held vertically and struck with a hammer. Describe how you would test whether the rod is magnetized. Which end should become an S-pole? Why strike it with the hammer? Test both ends of a rod not struck with a hammer.

2. A circular disc of wrought iron is placed between the opposite poles of two bar-magnets, whose axes are in the same straight line with a diameter of the disc. Make a diagram of the field of force; also one for similar poles of the magnets.

3. A bar-magnet is fixed in a vertical position with its N-pole downwards, and several nails are suspended from it. A similar bar-magnet of equal strength is slid along it with the S-pole downwards. What will happen to the nails? Explain the action.

4. Will a bar-magnet, floated in water on a piece of wood, drift towards the north? Give reasons for your answer.

5. Compasses used in surveying are usually provided with a small adjustable weight, which is used to balance the needle. Why is it necessary to make the weight adjustable? If the weight is on the S-end of the needle, how would you move it to adjust a compass, which was last used in New Orleans, for work in Ottawa?

6. Compasses become more sluggish in their movement as they approach the north magnetic pole. Account for this.

Static Electricity

1. Use the Electron Theory to explain why a pith-ball is first attracted to and then repelled from a charged ebonite rod.

2. How can an electroscope be shielded from the action of an electrical machine working near it?

3. A charge is placed on a gold-leaf electroscope. Describe what will happen to the leaves when (*a*) an insulated plate, (*b*) an earth-connected plate, is brought near the knob of the electroscope.

4. Why is repulsion between an unknown body and an electrified pith-ball a better indication that the body is electrified than is attraction?

5. Is it possible for a body on which there is a small charge of electricity to be at a higher potential than a body on which there is a much greater charge? Explain what is meant by *potential* and by *capacity*.

6. An electrical line of force marks the path along which a free unit positive charge would move, when placed near a charged body. Draw the field of force for a charged two-plate condenser.

7. What is meant by electrostatic induction? If a heavy negative charge is slowly brought up to a positively charged gold-leaf electroscope, what will be the effect on the leaves? Give reasons.

8. What will be the effect of connecting a condenser across the spark-gap of an electrical machine, (*a*) on the brightness of the spark, (*b*) on the frequency with which the spark occurs?

9. A Leyden jar is held in the hand by the outer coating and the knob is touched to a terminal of an electrical machine. The jar is then placed on a table. Explain why you receive a shock on touching the knob, and why no shock is felt if the jar is placed on a dry cake of rosin.

10. Compare the maximum capacity of the twenty-three plate variable condenser (Fig. 570) with that of a three plate "vernier" condenser, the condensers being identical except for the number of plates. (The twenty-three plate condenser has twelve fixed and eleven moving plates; the three plate condenser has two fixed and one moving).

Electrolysis

1. In calibrating an ammeter a certain current was found to deposit 0·7 gm. of silver in 40 min. What was the strength of the current?

2. An ammeter indicated 5 amperes while a current which deposited 6·2 gm. of copper in 1 hour was flowing through it. Find the error in the ammeter reading.

3. How much hydrogen and how much oxygen will be set free in a water voltameter by a current of 8 amperes flowing for 15 min.?

4. How long must a current of 80 amperes flow to refine one ton of copper?

5. The same current is passed through three electrolytic cells, the first containing acidulated water, the second a solution of copper sulphate, and the third a solution of silver nitrate. What weight of hydrogen and what weight of oxygen will be liberated in the first cell; and what weight of copper will be deposited at the cathode of the second cell; when 11·183 grams of silver are deposited on the cathode of the third cell?

Ohm's Law and Resistance

1. A flash-lamp has a resistance of 12 ohms and is lighted by a battery of 3 cells in series, each having an E.M.F. of 1·5 volts and an internal

resistance of 2 ohms. The output of the battery is ½ ampere-hour. How many flashes, each five seconds long will the lamp give before a new battery is required?

2. Four cells are joined in series. Each cell has an E.M.F. of 1·5 volts and an internal resistance of 3 ohms. Calculate the current which flows when the terminals of the battery are joined by a wire 60 ft. long, having a resistance of 12 ohms. Find also the p.d. between two points on the wire 10 ft. apart.

3. Two wires are joined in parallel and have a joint resistance of 3 ohms. If one wire has a resistance of 12 ohms, find the resistance of the other.

4. A cell having an internal resistance of 0·2 ohm is connected to an external circuit having a resistance of 2 ohms and including an ammeter. The difference in potential between the terminals of the cell is found to be 1·25 volts. What current will the ammeter indicate? What is the E.M.F. of the cell?

5. What is the resistance of an electric heater which allows 5 amperes to flow through it when connected to a 110-volt circuit? What current will flow through the heater when an electric lamp whose resistance is 110 ohms is connected (*a*) in series, (*b*) in parallel with it?

6. Calculate the unknown resistance for each of the following measurements with a Wheatstone Bridge (§ 600).

(1)	A = 19,	B = 10,	C = 100 ohms;
(2)	A = 187,	B = 1,	C = 1000 ohms;
(3)	A = 234,	B = 1000,	C = 10 ohms;
(4)	A = 3,	B = 1,	C = 1000 ohms.

7. Find the unknown resistance for each of the following measurements with a Slide-wire Bridge (§ 601).

(1)	A = 23 ohms,	PN = 40,	= 60 cm.;
(2)	A = 30 ohms,	PN = 20,	= 80 cm.;
(3)	A = 78 ohms,	PN = 48,	= 52 cm.;
(4)	A = 125 ohms,	PN = 63,	= 37 cm.

8. Find the resistance at 20°C. of 6 miles of copper wire 50 mils. in diameter (§ 602).

9. What length of No. 14 copper wire has a resistance of 10 ohms? (§§ 602, 603).

10. What current will pass through 300 yds. of No. 18 copper wire when connected to a storage battery whose E.M.F. is 2·2 volts and whose internal resistance is negligible? (§§ 602, 603.)

Electrical Energy and Power

1. An electric range takes 10 amperes at 220 volts pressure. Find the cost of using it for 2 hours at 5c. per k.w.h.

2. On May 1 a meter read 8764 k.w.h., and on June 1, 8876 k.w.h. Make out the bill for May at 7c. per k.w.h.

3. A watt-hour meter registered 2 k.w.h. in 2 hours when the E.M.F. was 110 volts and the current flowing through the "load" was 10 amperes. Find the error in the meter reading.

4. An electric motor which actually developed 2 horse-power required 16·5 amperes at an E.M.F. of 110 volts. Find the efficiency of the motor.

5. An electric fan requires 0·25 ampere at an E.M.F. of 110 volts. How much will it cost to run it for 5 days, 10 hours per day, in a town where electric energy costs 8c. per k.w.h.?

6. A 32 c.p., 102-volt lamp requires 1·25 watts per candle. Find the current which passes through the lamp and the cost of using it for 5 hours at 5c. per k.w.h.

7. What is the resistance of a 40-watt, 110-volt lamp? How many such lamps can be operated by a 5 k.w. dynamo?

8. In a transformer the input is 5 amperes at 2200 volts when the output is 98 amperes at 110 volts. Find the efficiency of the transformer.

9. A heating coil having a resistance of 50 ohms is connected to a 100-volt circuit and is placed in 1000 gm. of water at 0°C. Find the temperature of the water 10 min. later.

10. A 60-watt, 120-volt lamp is immersed in 500 gm. of water at 10°C., and the current is turned on for 30 min. Find the new temperature of the water.

ANSWERS TO NUMERICAL PROBLEMS

PART I—INTRODUCTION

Page 10. **1.** 2,500,000 mm. **2.** 299,731 km. **3.** 3,900,000 sq. cm. **4.** 29·92 in. **5.** 1000 l.; 1,000,000 c.c. **6.** 183·49 m. **7.** 65·4 cents. **8.** 6,465 kg. **9.** The former. **10.** 20·83 cents. **11.** 7899·8 mi.; 7926·8 mi. **12.** 11·37 sec.

Page 20. **1.** 1·47 kg. **2.** 54·05 c.c. **3.** 2·7 gm. per c.c.; 2·7; 168·5 pd. per cu. ft. **4.** 12 kg. **5.** 0·77 gm. per c.c.; 0·77; 48·05 pd. per cu. ft. **6.** 0·8. **7.** 1·072 gm. per c.c. **8.** 519·5 gm. **9.** 21·59 gm. per c.c.; 46·32 c.c. **10.** 1·99 mm.

PART II—MECHANICS OF FLUIDS

Page 29. **4.** $312\frac{1}{2}$ gm. **5.** 800 kg. **6.** 11,550 lb. **7.** 11·46 pd. per sq. in.

Page 35. **1.** 36 kg. **2.** 184·3 ft. (nearly). **3.** 92·43 ft. **4.** $14{,}501\frac{1}{3}$ pd. per sq. in. **5.** 3 tons. **6.** 173·31 ft.

Page 40. **1.** 62·5 pd.; 97·5 pd. **2.** 4·566 pd. **3.** 2·5 kg. **4.** 4·9 gm. **5.** $\frac{2}{15}$. **6.** 600 gm. **7.** $\frac{1}{4}$. **8.** 1562·5 lb. **9.** $3906\frac{1}{4}$ lb. **10.** 27·5 pd. **11.** $133\frac{1}{3}$ c.c. **12.** 4·8 c. ft.

Page 46. **1.** 20 c.c.; 6; 0·8. **2.** 20 c.c. **3.** $\frac{1}{4}$. **4.** $\frac{3}{7}$. **5.** $\frac{2}{3}$ gm. per c.c. **6.** 25 cm. **7.** (*a*) $\frac{5}{8}$; (*b*) $\frac{5}{6}$; (*c*) $6\frac{2}{3}$ cm. **8.** $\frac{8}{9}$.

Page 47. **3.** 196·08 m.; 2000 kg.; 44·1 pd. per sq. cm.

Page 50. **1.** 413·76 kg.; 912·34 lb. **2.** 1·273 gm. **3.** 796·2 gm. **5.** 3873·6 lb.

Page 59. **1.** 12·92 m. **2.** 1275 pd. **3.** 4·969 mi. **4.** 10,200 kg.

Page 68. **5.** 2907·75 kg. **6.** 2683 kg. **7.** 1334·5 kg. **8.** 4967 lb. **9.** 2360 lb.

Page 71. **3.** $6\frac{2}{3}$ cu. ft. **4.** 22·85 l. **5.** 75,283 cu. in. **6.** $483\frac{1}{3}$ in. of mercury. **7.** $562\frac{1}{2}$ mm. **8.** 174 in. of mercury. **9.** 0·0001259 gm. per c.c. **10.** 101·34 gm. **11.** $3·60. **12.** (*a*) 30 atmospheres; (*b*) 292·1 m.

Page 86. **1.** (*a*) $\frac{2}{3}$; (*b*) $\frac{8}{27}$. **2.** $\frac{4}{5}$. **3.** $1\frac{1}{2}$. **4.** 12·92 m.

Page 87. **2.** (*a*) Height of mercury barometer; 13·6 times height of mercury. **3.** $219\frac{1}{9}$ in. **9.** 31·2 pd. per sq. in.; 32·03 pd. per sq. in. **10.** 60 gm. per sq. cm.

PART III—MECHANICS OF SOLIDS

Page 94. **1.** 24 mi. per hr. **2.** $32\frac{5}{11}$ mi. per hr. **3.** 2898·44 mi. **4.** 88 ft. per sec. **5.** 108 km. per hr. **6.** 11 mi. per day. **7.** $2\frac{9}{14}$ mi. per day. **8.** 48 mi. per hr. **9.** 45 mi. **10.** 1413·72 m. per min. **11.** $5 \cdot 09 \times 10^{13}$ mi. (1 yr. = 365 d.)

Page 96. **1.** 20 ft. per sec.; 30 ft. per sec. **2.** 22 sec. **3.** $-5\frac{13}{15}$ ft. per sec. per sec. **4.** 5 m. per sec.; $-\frac{5}{6}$ m. per sec. per sec. **5.** $2\frac{17}{54}$ cm. per sec. per sec. **6.** $-\frac{1}{12}$ ft. per sec. per sec. **7.** 32·19 ft. per sec. per sec.

Page 98. **1.** 90 ft. per sec.; 1350 ft. **2.** 3·5 mi.; 0·176 ft. per sec. per sec. **3.** $2\frac{2}{3}$ mi. **4.** 484 ft. **5.** 400 m. **6.** $-14\frac{2}{3}$ ft. per sec. per sec. **7.** 120 ft. per sec. **8.** (*a*) $9\frac{1}{6}$ ft. per sec. per sec.; 48 sec.

Page 100. **1.** 980 cm. per sec. per sec. **2.** 192 ft. per sec.; 576 ft. **3.** 128 ft. per sec. **4.** 7·82 sec.; 4·37 sec. **5.** $759\frac{3}{8}$ ft.; $33\frac{3}{4}$ sec. **6.** (*1*) 4 sec.; (*2*) 7840 cm. **7.** 144 ft. or 44·1 m. **8.** (*1*) 160 ft. per sec. or 49 m. per sec.; (*2*) 400 ft. or 122·5 m.; (*3*) 144, 256, 336, 384, 400 ft. or 44·1, 78·4, 102·9, 117·6, 122·5 m.

Page 103. **2.** 14, 8, 11·4 ft. per sec. **4.** (*a*) 62·4 cm. per sec.; (*b*) 68·1 cm. **5.** 7·55 ft. per sec. **6.** 25 mi. per hr. **7.** 76·2 ft. per sec. **8.** (*a*) 264 yards from *B*; 3 min.; (*b*) $3\frac{3}{4}$ min.

Page 109. **1.** 3:2. **2.** 5:4. **3.** 525:256.

Page 112. **1.** 1, 2, 10 cm. per sec.; 1 cm. per sec. per sec. **2.** 0·1, 0·2, 1 cm. per sec.; 0·1 cm. per sec. per sec. **3.** 10, 20, 100 cm. per sec.; 10 cm. per sec. per sec. **4.** 5, 10, 50 cm. per sec.; 5 cm. per sec. per sec.; 20,000 units. **5.** 5 gm.; 2 cm. per sec. per sec.

Page 113. **1.** 50 ft. from house. **2.** 1250 m. per sec. **3.** 19·6 m. per sec.; 1250·15 m. per sec.

Page 115. **1.** 1 ft. per sec. **2.** 25 m. per sec. **4.** 11·72 ft. per sec. **7.** 15 ft. per sec. **9.** 3220 ft. per sec. **10.** 1:6; 3 ft., 18 ft.

Page 121. **1.** 70 cm. mark. **2.** 6 ft. from fulcrum. **3.** 20, $10\sqrt{3}$ ft. pound units. **4.** $16\frac{1}{4}$ pd. **5.** $70\frac{7}{12}$ lb.; $50\frac{5}{12}$ lb. **6.** 15 lb.; 10 lb.

Page 124. **1.** 39 pd. **2.** 15 lb. **3.** 155 pd.; 19° (nearly). **4.** 48 pd., 64 pd. **5.** 752 pd. **6.** 904·5 pd.

Page 128. **1.** Doubled. **2.** $1 \cdot 25 \times 10^5$ mi. **3.** $44\frac{4}{9}$, 25, 16 kg. **4.** 0·37 pd.

Page 132. **1.** 100,000 ergs. **2.** 1800 ft.-pd. **3.** 50,000 ft.-pd. **4.** $\frac{1}{245}$ kg.-m. **5.** 528,000 ft.-pd.

Page 135. **2.** $\frac{4}{15}$ h.p. **3.** $\frac{35}{44}$ h.p. **5.** 80·568 k.w. **6.** 7200 ft.-pd.; $\frac{36}{55}$ h.p. **7.** 20 h.p. **8.** 3675×10^7 ergs. **9.** 8 ft. **10.** 7·58 h.p. **11.** 1 k.w.h. = $3 \cdot 6 \times 10^6$ joules. **12.** 4 cents.

Page 142. **10.** 10 in. from 1-lb. weight. **11.** 5 ft. **12.** 40 cm. from 12 kg. pail; $40\frac{10}{21}$ cm. from 12 kg. pail.

Page 145. **4.** 45 pd. **6.** 396,000 ft.-pd. **7.** $\frac{1}{15}$. **8.** (*a*) $51{,}020\frac{20}{49}$ gm.-cm.; (*b*) 6000F.; (*c*) $8\frac{74}{147}$ gm.; (*d*) $\frac{25}{1176}$. **9.** (*a*) 1452 pd.; (*b*) 2080 pd.; 104·7 ft.; (*c*) 36,300 pd.

Page 151. **1.** $1\frac{1}{4}$ lb. **2.** 90 lb., 120 lb. **3.** $37\frac{1}{2}$ pd. **4.** 225 pd. **5.** 22·5 pd. **6.** 90 pd.

Page 157. **1.** 4. **2.** **3.** 60 pd. **6** (*a*) 100 pd.; (*b*) 100 lb. for rope 2–3; 200 lb. for rope 1–4; (*c*) 200 lb.; (*d*) 400 lb. **7.** 250 pd.; 12,500 ft.-pd.

Page 161. **1.** $26\frac{2}{3}$ pd. **2.** $53\frac{1}{3}$; 6400 lb.

Page 163. **2.** $20\frac{5}{9}$ pd. **3.** (*1*) 95 pd.; 200 pd. (*2*) 95 pd., 105 pd. **4.** 400 pd.

PART IV—SOME PROPERTIES OF MATTER

Page 179. **1.** $3\frac{1}{3}$ sq. km. **2.** 100,000,000 yrs. (approx.). **3.** 2000.

PART V—HEAT

Page 206. **6.** 9, 27, 63, 117. **7.** 5, 15, 20, $52\frac{7}{9}$. **8.** 45. **9.** 15. **10.** 50°, 68°, 89·6°, 167°, −4°, −40°, −459·4°. **11.** 15°, 5°, 0°, −10°, $-17\frac{7}{9}$°, −30°. **12.** $38\frac{8}{9}$.

Page 210. **3.** 0·00000733. **4.** 4·0002 ft. **5.** 1·000342 m. **6.** 2·97 ft. **8.** 120·0216 sq. in.

Page 213. **3.** 8·1296 cu. ft. **4.** 0·00018. **5.** 0·000515.

Page 218. **1.** (*a*) Double; (*b*) Same; (*c*) One-half. **2.** (*a*) Double; (*b*) Same. **3.** 28·55 l. **4.** 107·6 c.c. **5.** 155·1 pd. per sq. in. **6.** 17·53 pd. per sq. in. **7.** (*a*) 32·8°C.; (*b*) −22·8°C. **8.** 27·3°C. **9.** 108·87 l. **10.** $322\frac{2}{9}$ c.c. **11.** 1520 mm. mercury. **12.** No change. **13.** 1050 c.c. **14.** 1779 :1465. **15.** 0·837 gm.

Page 222. **1.** 1625 cal. **2.** 3,000 cal. **3.** 23°C. **4.** 10C. deg. **6.** 45°C. **7.** 9·6°C. **8.** 40°C. **9.** 110°F. **10.** $10.

Page 224. **1.** 12,250 cal. **2.** 6000 cal. **3.** $3166\frac{2}{3}$ cal. **4.** 8160 cal. **5.** 34,627·5 B.T.U.

Page 226. **1.** 5·6 cal. **2.** Mercury. **3.** 36 cal.; 36 gm. **4.** 0·094. **5.** 0·694. **6.** 9,600 cal. **7.** 950·16 cal. **8.** 226,000 cal. **9.** 27·9 cal.

Page 230. **1.** 0·113; iron. **2.** 0·113. **3.** 30,225 cal. **4.** 0·678. **5.** 0·748. **6.** 47·0°C. **7.** 3·17°C. **8.** 12·42°C. **9.** (*a*) 11·28 gm.; (*b*) 3·2 gm.; (*c*) 1·699 gm.

Page 237. **6.** 2800 cal. **7.** 1,200,000 cal. **8.** 2,185 cal. **9.** 80 gm. **10.** 79·38. **11.** 80. **12.** 0·09. **13.** $1{,}111\frac{1}{9}$ gm. **14.** 166·15 gm. **15.** 12·05 gm. **16.** $59\frac{1}{11}$°C. **17.** 144 B.T.U. **18.** 30,000 B.T.U.

Page 247. **6.** 19,980 cal. **7.** 183,600 cal. **8.** 28,125 cal. **9.** 232,140 cal. **10.** 539·7. **11.** 540. **12.** 10 gm. **13.** $3\frac{1}{8}$ gm. **14.** 44·65°C. **15.** 22,050 cal. **16.** 37·04 gm.

Page 263. **6.** 55·8%; 10·3°C. **7.** (*a*) 72·3%; (*b*) 61·7%; (*c*) 55·9%.

Page 290. **4.** 2500 ft.-pd.; 3·21 B.T.U. **5.** 3,736,250 l. **6.** 2·39 $\times$ 10^3 cal. (approx.) **7.** 77,763·5 B.T.U. **8.** 78·06 kg. **9.** 1038·8 lb. **10.** 25·97%. **11.** 16·9%.

PART VI—SOUND

Page 297. **1.** 335, 338, 356 m. per sec. **2.** 1024·3 ft. per sec. **3.** 5595 ft. **4.** 5545 yd. **5.** 4516 ft. **6.** 1680, 2240 ft. **7.** 4707·4 ft. per sec.

Page 311. **1.** 2·24 ft. **2.** 1693·5. **3.** 16,935 ft. per sec. **4.** 3474·7 m. per sec. **5.** 4290·2 ft. per sec. **6.** 4064 m. per sec.

Page 319. **4.** 3·81 sec. **6.** 1259 ft. **7.** 1678·5 ft. **8.** 10,593 ft.

Page 325. **2.** 260; $4\frac{4}{13}$ ft. **3.** 576. **4.** 1044. **5.** 640, 768, 1024. **6.** C, 256; E, 320; C′, 512. **7.** F, 400; A, 500. **8.** $271\frac{1}{5}$. **9.** 7·07 cm. **10.** G′, E″.

Page 333. **2.** 250, $66\frac{2}{3}$ cm. **3.** 320. **4.** 36 pd. **5.** 9 :10. **6.** 3 :2. **7.** $11\frac{1}{4}$ pd.; $33\frac{1}{3}$ cm. **8.** 100. **9.** 60. **10.** 96 pd.

Page 342. **3.** $1093\frac{1}{3}$ ft. per sec. **4.** 13·23; 26·46. **5.** 10·49 in.

Page 345. **2.** 300, 500. **5.** 6·49 in. **6.** 1·5 ft. **7.** 3 :2. **10.** 109, 86, 420.

Page 355. **5.** 509 or 515.

PART VII—LIGHT

Page 374. **1.** 2·4 in. **2.** $62\frac{1}{2}$ ft. **7.** 185,856 miles per sec. **8.** 7·44 times. **9.** (*a*) 176·86 yrs.; (*b*) 13·89 yrs.; (*c*) $8\frac{1}{3}$ min. **10.** 5,047,953,696 $\times$ 10^4 mi.; 2,582,673,984 $\times$ 10^5 mi.

Page 379. **2.** 1, $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{100}$ foot-candles. **3.** 9 foot-candles. **4.** 1 foot-candle; 4 foot-candles. **5.** $1\frac{1}{4}$ foot-candles. **6.** 32 c.p., $1\frac{1}{4}$ watts per c.p. **8.** 16 :49. **9.** 3 ft. **10.** $8\frac{1}{2}$ ft. (nearly). **11.** $63\frac{1}{4}$ ft. **12.** 180 c.p.

Page 384. **1.** 16 c.p. **2.** 8 candles. **3.** 9 c.p. **4.** 16 c.p. **5.** 720 c.p. **6.** 56·56 in. **7.** 51·96 in. from the screen. **8.** 121 :400. **9.** 25 :4. **10.** 2 ft. from candle towards gas-flame and 6 ft. from candle in opposite direction.

Page 392. **1.** 20 ft. in front and facing the same way; it will appear to go forward at 30 mi. per hour; 90 mi. per hour; $\frac{1}{2}$ mile. **4.** 7 images; 5 images; 3 images. **8.** 110°; 4°.

Page 414. **5.** 75,304 mi. per sec.; 0·405. **6.** 139,500 mi. per sec.; 124,000 mi. per sec.; $\frac{9}{8}$.

Page 418. **6.** 30°, $48\frac{1}{2}$°. **8.** 1·52.

Page 434. **7.** 4, $\frac{1}{4}$. **8.** 6 feet. **12.** 50 cm.; $33\frac{1}{3}$ cm. **13.** $22\frac{2}{9}$ cm; 40 cm. **14.** 120·5 cm. **15.** 375 cm.

Page 454. **6.** 30 cm.

PART VIII—ELECTRICITY AND MAGNETISM

Page 482. **6.** 100°; 280°. **7.** $\frac{5}{6}$ mi.

Page 531. **4.** 20 hr.; $26\frac{2}{3}$ hr. **5.** 15 hr.

Page 534. **1.** 2·3688 gm.; 8·5176 gm. **2.** 0·3744 gm.; 2·9952 gm. **3.** 4·18324 l.; 2·09162 l. **4.** 6·03 amperes. **5.** 4·9987 amperes. **6.** 0·051 amperes. **7.** 1·994 amperes. **8.** 50 min. 39·5 sec. **9.** 0·6102 gm. **10.** 2·5 ampere-hours.

Page 538. **1.** 550 watts. **2.** 6 amperes. **3.** 5·227 amperes. **4.** 0·136 amperes. **5.** 396 watts; 0·53 h.p. **6.** 0·227 amperes; 0·333 amperes; 0·521 amperes. **7.** 2321 watts; 3·111 h.p. **8.** 12·995 k.w. **9.** 6·6 k.w.; 8·847 h.p.

Page 541. **1.** $\frac{1}{3}$ amp. **2.** $\frac{1}{2}$ amp. **3.** 208 ohms. **4.** 0·19 ohms. **5.** 22 volts. **6.** 13·5 volts.

Page 543. **1.** $8\frac{1}{3}$ amp.; 80 volts; 20 volts. **2.** $\frac{1}{2}$ amp.; $\frac{1}{2}$ volt. **3.** 1 volt; 1 volt; 102 volts. **4.** 113 volts.

Page 604. **1.** 250 ft. **2.** 72 ohms. **3.** 20·31 ohms. **4.** 22·5 m. **5.** 135·9 yd. **6.** $\frac{2}{3}$ mm. **7.** 2·653 mm. **8.** 1080 yd. **9.** 32·48 microhms. **10.** 20·1 ohms; 75·84 ohms.

Page 606. **1.** $6\frac{2}{3}$ ohms; $\frac{2}{3}$, $\frac{1}{3}$. **2.** $8\frac{1}{12}$ ohms; $\frac{63}{73}$ ohms. **3.** 4 ohms. **4.** 100 ohms. **5.** $2\frac{1}{12}$ amp.; $\frac{12}{25}$; 48 ohms. **6.** 100 ohms. **7.** $\frac{1}{n+1}$. **8.** 9 :25.

Page 608. **1.** 3 amp. **2.** 2·87 amp. **3.** 49 cells. **4.** 0·15 amp.

Page 612. **1.** 360,000 coulombs. **2.** 12·5 k.w. **3.** 13·75 k.w.; 18·43 h.p. **4.** 99,840 watt-hours; \$7·99. **5.** 3·3 cents. **6.** 11 lamps. **7.** $2\frac{8}{746}$ h.p. **8.** 90%. **9.** 10,368 calories.

REVIEW PROBLEMS

Measurement. **1.** 70 mi. (more nearly 69·6). **2.** 64 km. per hr. **3.** 0·882 cm. **4.** 0·60 in. **5.** 205 lb. **6.** 0·37 cu. in.; 20 cents. **7.** 8·13. **8.** (*a*) 0·791 kg.; (*b*) 13·6 kg.; (*c*) 0·48 kg. **9.** 468 tons; 424,560 kg. **10.** 936 lb.

Mechanics of Fluids. **1.** $43\frac{1}{3}$ pd. per sq. in. **2.** 64. **3.** 109·5 gm; 15 c.c. **4.** 2404 kg. **5.** 1036·32 gm. per sq. cm.; 14·71 pd. per sq. in. **6.** 800 c.c. **7.** $26\frac{2}{3}$ pd. per sq. in. **8.** 100·1 pd. **9.** 42 pd. per sq. in. **10.** 202,176 pd.; same.

Mechanics of Solids. **1.** 480 ft. per sec. **2.** 90 ft. **3.** 9 ft. from 20 lb. mass. **4.** 2600 pd. **5.** 200 dynes. **6.** 10 gm. **7.** 19,800 gal. **8.** 2,000,000 pd. **9.** $1642\frac{2}{3}$ ft.-pd. **10.** 150 pd.

Expansion by Heat. **1.** 0·000020. **2.** 3·53 cm. **3.** 172·27 c.c. **4.** 24·30 gm. **5.** 34·49°C.

Specific Heat. **1.** 12·53°C.; 10 gm. **2.** 19·9°C. **3.** 50°C. **4.** 50°C. **5.** 0·513.

Latent Heat. **1.** 0·113. **2.** $7\frac{1}{2}$°C. **3.** 80·09. **4.** 11·93°C. **5.** 40°C. **6.** 244·60 gm. **7.** 907,500 cal. **8.** 128,880 B.T.U. **9.** 199·8 cal. **10.** $49\frac{1}{3}$°C.

Velocity of Sound. **1.** 2984 yd. **2.** 3750 yd. **3.** 52·5 in. **4.** 33·87 in. **5.** 1000 ft. per sec.

Vibrating Strings. **1.** 640; 40 cm. **2.** 24 cm. **3.** 80 pd. **4.** 1:5. **5.** C″.

Resonance; Organ Pipes. **1.** 337·92 m. per sec. **2.** 35 in. **3.** 21·17 in. **4.** 120 cm.; 285. **5.** 20 cm.

Shadows. **2.** 150 ft. **3.** 200 ft. **4.** 80 ft. **5.** $\frac{25}{186}$ sec.; 32·74 hr.

Illumination. **1.** 1:10. **2.** $44\frac{4}{9}$ cm. from 16 c.p. lamp. **3.** 2500 c.p. **4.** 9:25. **5.** 6·67 times.

Plane Mirrors. **2.** 48 in. **3.** In plane N.E.–S.W. **4.** 45°. **5.** Making an angle of 30° with mirror.

Curved Mirrors. **4.** 18·75 cm. to right of mirror; mag. $\frac{1}{4}$. **5.** 3·2 cm. **6.** 10 cm. to left of mirror; $2\frac{2}{3}$ cm. **7.** 30 cm. to right of mirror; 4·5 cm. **8.** (*a*) $3\frac{3}{7}$ in. to left of mirror; $\frac{3}{7}$ height of candle; (*b*) $4\frac{4}{11}$ in. to left of mirror, $\frac{3}{11}$ height of candle. **9.** 6 ft.

Refraction. **1.** 139,849·6 mi. per sec.; 121,568·6 mi. per sec. **2.** $16\frac{1}{2}$°. **3.** 6 ft. x 9 ft. **4.** 20 cm. from lamp; $16\frac{2}{3}$ cm. **5.** 6 dioptres; $16\frac{2}{3}$ cm. **6.** 30 cm.; 6 cm. **7.** $40\frac{1}{2}$°. **8.** 39°. **9.** 3 in.; 5·76 in. **10.** $51\frac{3}{7}$ in.

Static Electricity. **10.** 11:1.

Electrolysis. **1.** 0·261 amp. **2.** 0·235 amp. **3.** 0·07488 gm.; 0·59904 gm. **4.** 9574 hr. **5.** 0·104 gm.; 0·832 gm.; 3·29 gm.

Ohm's Law and Resistance. **1.** 1440. **2.** $\frac{1}{4}$ amp.; $\frac{1}{2}$ volt. **3.** 4 ohms. **4.** 0·625 amp.; 1·375 volts. **5.** 22 ohms.; $\frac{5}{6}$ amp.; 5 amp. **6.** (*1*) 1·9 ohms; (*2*) 0·187 ohm; (*3*) 23,400 ohms; (*4*) 0·003 ohm. **7.** (*1*) $15\frac{1}{3}$ ohms; (*2*) 7·5 ohms; (*3*) 72 ohms; (*4*) 212·84 ohms. **8.** 131·79 ohms. **9.** 3951 ft. **10.** 0·382 amp.

Electrical Energy and Power. **1.** 22 cents. **2.** $7·84. **3.** 0·2 k.w.h. **4.** 82·2%. **5.** 11 cents. **6.** $\frac{1}{3}$ amp.; 1 cent. **7.** 302·5 ohms; 125. **8.** 98%. **9.** 28·8°C. **10.** 61·8°C.

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